Journal of Food Quality

Quality and Operations Management in Food Supply Chain

Guest Editors: Yong He, Dong Li, Sarah J. Wu, and Chunming Shi

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Lead Guest Editor: Yong He
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Contents

Quality and Operations Management in Food Supply Chain
Yong He, Dong Li, Sarah J. Wu, and Chunming Shi
Editorial (2 pages), Article ID 9871379, Volume 2018 (2018)

The Impact of Food Quality Information Services on Food Supply Chain Pricing Decisions and Coordination Mechanisms Based on the O2O E-Commerce Mode
Xiaoqiu Yu and Xiaoxue Ren
Research Article (18 pages), Article ID 8956820, Volume 2018 (2018)

Quality and Operations Management in Food Supply Chains: A Literature Review
Yong He, Hongfu Huang, Dong Li, Chunming Shi, and Sarah J. Wu
Review Article (14 pages), Article ID 7279491, Volume 2018 (2018)

Quality Risk Evaluation of the Food Supply Chain Using a Fuzzy Comprehensive Evaluation Model and Failure Mode, Effects, and Criticality Analysis
Libiao Bai, Chunming Shi, Yuntao Guo, Qiang Du, and Youdan Huang
Research Article (19 pages), Article ID 2637075, Volume 2018 (2018)

How Does Suppliers' Fairness Affect the Relationship Quality of Agricultural Product Supply Chains?
Yuling Sun, Zehua Liu, and Hui Yang
Research Article (15 pages), Article ID 9313068, Volume 2018 (2018)

Bundle Pricing Decisions for Fresh Products with Quality Deterioration
Yan Fang, Yiping Jiang, and Xingxing Han
Research Article (8 pages), Article ID 1595807, Volume 2018 (2018)

Vertical Cost-Information Sharing in a Food Supply Chain with Multiple Unreliable Suppliers and Two Manufacturers
Junjian Wu, Haiyan Wang, and Henry Xu
Research Article (14 pages), Article ID 6792545, Volume 2017 (2018)

The Pricing Strategy of Oligopolistic Competition Food Firms with the Asymmetric Information and Scientific Uncertainty
Li Zhao, Changwei Wang, Xiaohui Peng, Bin Liu, and David Ahlstrom
Research Article (14 pages), Article ID 4628905, Volume 2017 (2018)

Economic Order Quality Model for Determining the Sales Prices of Fresh Goods at Various Points in Time
Po-Yu Chen
Research Article (12 pages), Article ID 6967501, Volume 2017 (2018)

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Editorial

Quality and Operations Management in Food Supply Chain

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Quality of food products changes continuously during various stages like transportation and storage, which brings challenges to the operations management of food supply chains. This special issue focuses on the quality and operations management issues in food supply chain management. The articles in this special issue provide important insights for firms to improve operations process control, reduce waste, lower cost, meet customers' expectation, or mitigate food safety risks. Y. He et al. present a literature review on quality and operations management problems in food supply chains. In the review, gaps are identified in this research area along with suggestions and directions for future research.

Evaluating quality risk levels in food supply chains can reduce quality information asymmetry, minimize food quality incidents, and promote integrated regulations for food quality. However, robust and quantitative methods are rarely reported for assessing the risk level of every link in food supply chains and evaluating the overall risk. As such, there is a need to provide effective guidance for the quality risk evaluation in the whole food supply chain. To address this problem, L. Bai et al. study the food supply chain using a quality risk evaluation indicator system. They develop a mathematical model based upon the fuzzy comprehensive evaluation model (FCEM) and failure mode, effects, and criticality analysis (FMECA) so as to evaluate the quality risk level in the food supply chain. They conduct computational experiments to verify the effectiveness and feasibility of this proposed model through a questionnaire survey.

Quality change affects customers' preferences for food products. To enhance their profitability, firms usually utilize behavior-based pricing strategies. Due to the lack of information about food freshness, consumers' decision-making highly depends on sales prices and manufacturing and expiry dates of items. P.-Y. Chen develops an EOQ model assuming that dealers are able to determine the sales price at each point of time and predict customers' intention of buying food items in varying freshness. As a result, dealers can set an optimal inventory cycle and allocate a weekly sales price for each time point to maximize the profit per unit time. This model allows dealers to discover the optimal sales prices and to identify the optimal solution for fresh goods retailers to conduct immediate price control. Since bundling strategy is an efficient way to reduce storage cost and to meet customer quality requirements, Y. Fang et al. establish a nonlinear mixed integer programming model to formulate the bundle pricing problem for fresh products, where they assume that two or more fresh products can be sold together in one united price.

Information asymmetry is prevalent in food supply chains. On the one hand, it affects pricing or inventory decisions. On the other hand, consumers could not identify the real quality until purchasing and consuming the experience goods. In some cases, they may not know the quality or variety even after consuming the credence goods such as genetically modified (GM) food. In the context of asymmetric information and scientific uncertainty, L. Zhao et al. explore pricing strategies between two firms producing horizontally and vertically differentiated foods. The type of a firm's product is not public information, but its pricing decision may signal its product type to consumers. Additionally, they consider the scientific uncertainty as a risk with a known distribution, the expected potential net damage, and the volatility of risk. Their study aims to combine market mechanisms with government regulations to separate GM food from the conventional food conforming to consumer's right to know. J. Wu et al. consider a food supply chain with two competing manufacturers and multiple competing unreliable suppliers (i.e., multisourcing). While the suppliers compete on price, the manufacturers compete on quantity. They develop a stylized multistage game theoretic model to examine the impact of key parameters, including the level of yield uncertainty, two manufacturers' cost correlation, the correlated coefficient of suppliers' yield processes, and the number of suppliers on the manufacturers' willingness to vertical cost-information sharing. Empirically, Y. Sun et al. conduct a survey of 450 agricultural product suppliers and obtain some interesting results by statistically analyzing the impact of antecedents on fairness perception and the influence of fairness perception on relationship quality. They also analyze moderating effect of dependence on the impact path from fairness perception to relationship quality (i.e., trust and commitment).

The O2O (Online to Offline) business model has become more popular with the fast development of Internet and information technology. This business model has also been adopted by some food providers. X. Yu and X. Ren study a dual-selling model with an online food processing factory and an offline retailer under the impact of food quality information service. The study provides useful managerial implications to firms in the industry.

Overall, the above-mentioned studies significantly contribute to both literature and practice, which bridges the gaps in the research area of food supply chain management. We hope that readers of this special issue find the selected contributions interesting. We would be delighted if this special issue could serve as a strong driving force to push the future research on food quality and operations management in food supply chains to a higher level.

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Research Article

The Impact of Food Quality Information Services on Food Supply Chain Pricing Decisions and Coordination Mechanisms Based on the O2O E-Commerce Mode

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This paper considers the price conflict problem between the online channel of a food processing factory and the offline channel of the food retailers in food supply chains by analyzing the pricing decisions and coordination mechanisms between the food processing factory and food retailers under the influence of a food quality information service. First, the Stackelberg game method and the Bertrand game method are used to optimize the pricing decisions with the goal of maximizing the profits of the food processing factory and retailer. The analysis shows that the food quality information service level is positively correlated with the price of the factory's own channel, and the influence of the food quality information service level on the price of the food processing factory's or the food retailer's own channel is stronger than its influence on the price of a competitor's channel. Second, the food supply chain members' pricing decisions are analyzed using the case analysis method by considering practical problems in the food supply chain. The results indicate that the food processing factory should use the Stackelberg game to make pricing decisions. However, it is optimal for the food retailer to make pricing decisions under the Bertrand game, and the total profit of the food supply chain is optimized under centralized decision making. Finally, we use both the quantitative discount mechanism and the Stackelberg game method to analyze the profits obtained by the food processing factory and retailer. The results indicate that the food processing factory should implement a quantitative discount mechanism when the quantity discount coefficient is greater than 0.4, and the retailer should implement a quantity discount mechanism when the quantity discount coefficient is in the range of 0.25 to 0.4.

1. Introduction

The O2O mode refers to the combination of an online channel and an offline channel. A food quality information service is an important criterion in consumers' channel selection and purchase decisions. In this article, a food quality information service is provided by members of a food supply chain to provide consumers information about food quality. Zeithaml [1] reported that such information is delivered to consumers in different ways, and food quality information services can be distinguished in terms of having practical significance or symbolic significance. There is abundant food quality information that interests consumers, including price, brand, date of manufacture, appearance, signals of quality and safety, manufacturer, production environment, storage, and media promotion. In this article, the online channel that provides consumers with food quality information is a network platform that provides consumers basic food information, such as price, brand, production date, and whether the item is being sold at a discount, while the offline channel provides consumers food quality information by allowing them to experience shopping firsthand and personally examine the freshness of the food, among other visual inputs.

A food supply chain is a network structure formed by upstream and downstream enterprises, and it includes the food production and circulation processes involved in the products or services provided to consumers. Nianyugou Wangu Processing Co., Ltd., is located in Zhaoyuan farms, Daqing city, province of Heilongjiang, China. It is a food processing factory that uses a JD e-commerce platform in its Nianyugou flagship store (online channel) to sell products; at the same time, it also uses offline physical stores (offline channel) to sell products. Its success stems from its business philosophy, which involves the provision of services to retailers and consumers through its online and offline channels. The company aggregates consumer information obtained from food retailers and strives to respond to changes in consumer demand.

The research for this article is based on the food processing factory and a food retailer that provide food to consumers through online and offline channels, respectively. However, there are many problems in the food supply chain. On the one hand, the food quality information service level affects consumers' channel selection decision, and food retailers have a significant information advantage over the food processing factory in terms of food quality information. On the other hand, the food processing factory has a price advantage over the food retailers, resulting in price competition in the food supply chain. Therefore, this problem needs to be resolved to set reasonable sales prices and optimize and coordinate the profits in the food supply chain.

In recent years, food supply chains have experienced substantial changes [2]. Information is transmitted in a food supply chain to check the quality of the food, for example, by tracing the food upward or tracking it downward in the supply chain [3]. Moreover, the concepts of food quality information services and food safety are often viewed as two sides of the same coin [4]. Food safety has become very important for food quality information services [5, 6]. However, some authors have stated that traceability has not been implemented in systems to improve the food quality information [7]. Because of a decrease in liability claims, responsibilities along the supply chain can be precisely identified [3, 8].

Recent studies have focused on the quality, safety, and sustainability of food [9]. From a new perspective, sustainability in the food supply chain has been discussed [10–13]. Third-party certifications have facilitated patrons' evaluations of food and service quality [14]. However, the current practice of evaluating food contact surface cleanliness by sight and touch to meet regulatory requirements might be inadequate (Cunningham et al. 2017). In the food industry, food quality information is affected by food processing and logistics activities, such as transportation and packaging (Riccardo et al. 2017). Food quality depends on intrinsic and extrinsic factors, such as the storage temperature, concentration of oxygen, and relative humidity [15, 16].

The factors affecting food quality information services—customer service level and satisfaction, safety, sustainability, and cost-efficiency—are the primary targets of an effective food supply chain [17]. Food quality is significantly affected by the use of a standard (or nonstandard) container. The quality and taste of food products depend on both the food processing procedure and logistics, including transportation and packaging processes [18, 19]. The impacts of certain attributes of food service quality on consumers have been evaluated. Overall, consumers perceive that service quality attributes are more important than food quality attributes. [20]. In the food service industry, food processing factories receive food from manufacturing plants [21, 22].

Food service quality attributes, such as the wait time and the server's attentiveness and helpfulness, account for 31.8% of customers' satisfaction. Richard et al. investigated the importance of service quality in customers' selection of food products [23]. Many researchers have studied customers' satisfaction with restaurants' food services (Folinas et al. 2016). Awareness of and attitudes toward traceability in the food supply chain were examined within British small and medium-sized enterprises (SMEs) [24]. Because of the unique aspects of a hospital environment, consumers require higher food quality information when in a hospital [25]. In addition, reliable suppliers are chosen based on raw material specifications and supplier audits, thereby reducing the likelihood of contaminated products entering the market [21, 26]. However, testing must occur to verify that risk mitigation measures are working as expected. Therefore, a sampling plan must be designed [27, 28].

In summary, the literature related to this research has primarily focused on the impact of factors such as food quality, food safety, and food quality information on consumers' evaluations. However, with the development of e-commerce, food processing factories are providing consumers services through online channels, and food retailers are providing consumers services through offline channels, resulting in the online-to-offline (O2O) mode. The emergence of the O2O mode has brought the online and offline channels into competition. Therefore, the rational formulation of pricing decisions and coordination among the members of a food supply chain have become urgent problems. Based on the characteristics of a food supply chain, this paper considers a situation in which the online channel of a food processing factory cooperates with the offline channel of a food retailer to provide food quality information services.

Secondary food supply chains are based on the O2O mode. First, according to the demand function, this paper introduces the food quality information service level into the demand function, and based on transaction cost theory, the total profit function of the food processing factory, food retailer, and food supply chain is established. Second, we discuss the food supply chain's pricing decision under centralized decision making and decentralized decision making, and we obtain the optimal prices for the online and offline channels and the optimal profits for the food processing factory and food retailer. Then, we discuss the relationship between the food quality information service level and prices and profits. With the goal of optimizing the profitability of the food supply chain, we can establish a mechanism to coordinate a food supply chain quantitative discount and ensure a profitable relationship for the food processing factory and the retailer. Finally, the validity of the theoretical assumptions is verified using numerical simulations, and the coordination efficiency of the food supply chain is evaluated.

2. Materials and Methods

2.1. Model Description. Based on the supply chain management business philosophy of Nianyugou Wangu Processing Co., Ltd., this paper considers a situation in which the food processing factory is part of the food quality information services that a food retailer must review, and the food retailer

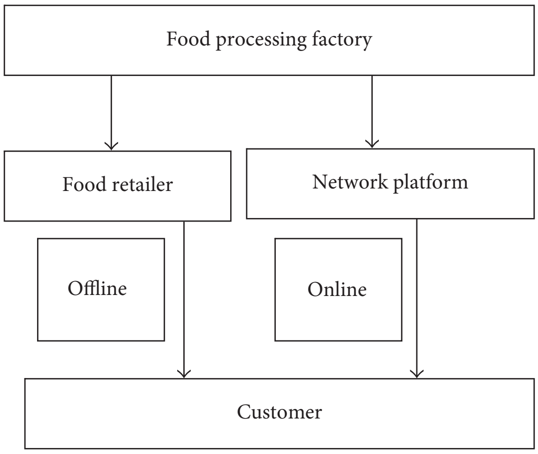

Figure 1: The structure of the food supply chain under the O2O mode.

receives the appropriate compensation, which is that the food processing factory cooperates with the food retailer in providing food quality information.

The food supply chain under the O2O mode consists of the online channel of the food processing factory and the offline channel of the food retailer. In a food supply chain dominated by a food processing factory, the food processing factory provides the food retailer with food at wholesale prices. Although the food processing factory sells its products through the food retailer's offline channel, it also sells food directly through an online channel, resulting in price conflicts between the two channels, as shown in Figure 1.

2.2. Framework of the Research Methodology. To solve the problem of the price conflict and to increase the coordination between the food processing factory and food retailers in the food supply chain, this article relies on game theory and establishes a Stackelberg game model and a Bertrand game model to determine the optimal price and profit of the two channels given the constraints. Matlab software is used to visualize the relationship between the variables.

As shown in Figure 2, first, this paper incorporates the food quality information service level into the demand function, and based on transaction cost theory, the total profit function of the food processing factory, the food retailer, and the food supply chain is established. Second, using the methods of the Stackelberg game and the Bertrand game, this paper analyzes the influence of food quality information services on price under centralized and decentralized decision making, respectively. Further, we obtain the optimal pricing decision for the food processing factory, food retailer, and food supply chain. Then, with the goal of optimizing the profitability of the food supply chain, we establish a food supply chain quantitative discount coordination mechanism. Finally, using Matlab software for a numerical simulation, we validate and optimize the relationship between the variables involved in the food supply chain.

Why did we choose these two models? When we conducted a survey among employees of Nianyugou Wangu Processing Co., Ltd., we found that the game relationship between the subjects involved in the food supply chain when making pricing decisions could be accurately reflected by the Bertrand and Stackelberg game models.

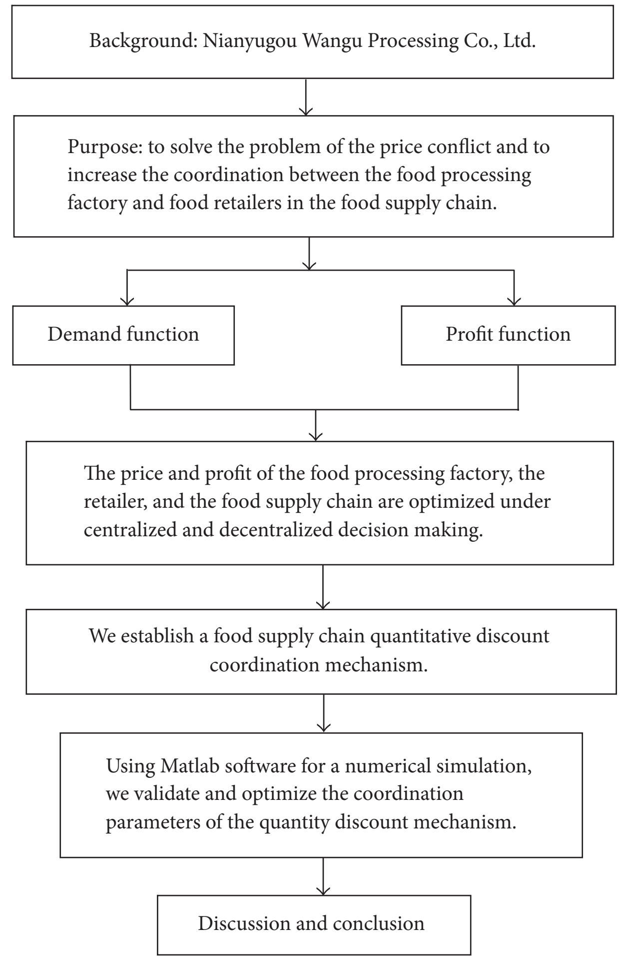

Figure 2: The roadmap of this paper.

2.2.1. Exogenous Parameters

a_i: The market size

c: The unit cost of the product

w: The wholesale price provided by the food processing factory to the food retailer

α_1: The market demand for the price level of the elasticity coefficient

α_2: The market demand for the food quality information service level of the elasticity coefficient

β_1: The market demand for the price level difference in the transfer coefficient

β_2: The market demand for the food quality information service level difference of the transfer coefficient.

2.2.2. Decision Variables

p_i: The sales price

s_i: The food quality information service level, where ($s_i \geq 0$) indicates the food quality information service level ($i = 1$, the online channel; $i = 2$, the offline channel) and $s_i = 0$, which means that food quality information services are not considered. The larger the value of s_i is, the higher the level of the food quality information service is, where ($0 < s_i \leq 5$) indicates a lower food quality information service level, ($6 < s_i < 15$) indicates a moderate food quality information service level, and ($s_i \geq 15$) indicates a high food quality information service level

η_i: The service cost coefficient of the food quality information

D_i: The demand

($i = 1$, the online channel; $i = 2$, the offline channel)

Π_i^j: The profit

where ($j = 1$, under the Bertrand game; $j = 2$ under the Stackelberg game; $j = 3$, under the centralized decision) ($i = 1$, for the food processing factory; $i = 2$, for the food retailer, and $i = 3$, for the food supply chain).

2.2.3. Contract Terms under Negotiation

k: The quantity discount coefficient.

2.3. Model Construction

Assumption 1. The wholesale price is determined by the market price.

Assumption 2. The impact of channel prices on demand is greater than the effect of price differences between the two channels. The impact of the level of a channel's food quality information service on demand is greater than the impact of the difference in the level of the food quality information service between the two channels.

Assumption 3. Assuming that the food quality information service level is certain, the food retailers' food quality information service costs are lower than the food processing factory's costs; that is, $\eta_2 < \eta_1$.

Assumption 4. The food processing factory provides consumers with food quality information services through the online channel of its own network platform, while the food retailer provides consumers with food quality information services through the offline channel.

Referring to the demand function constructed by Yao et al. [29, 30], introducing the factors of the food quality information service on demand, the linear demand function for both the online channel of the food processing factory and the offline channel of the food retailer can be expressed as follows:

$$\begin{aligned} D_1 &= a_1 - \alpha_1 p_1 + \alpha_2 s_1 + \beta_1 (p_2 - p_1) + \beta_2 (s_1 - s_2) \\ D_2 &= a_2 - \alpha_1 p_2 + \alpha_2 s_2 + \beta_1 (p_1 - p_2) + \beta_2 (s_2 - s_1). \end{aligned} \tag{1}$$

Referring to the model by Chen [31], we establish a function of the food quality information service cost as follows:

$$c(s) = \frac{\eta s^2}{2}. \tag{2}$$

The profit function of the food processing factory, the food retailer, and the total food supply chain can be expressed as follows:

$$\Pi_1 = (p_1 - c - c(s_1)) D_1 + (w - c) D_2 \tag{3}$$

$$\Pi_2 = (p_2 - w - c(s_2)) D_2 + (c(s_1) - c^*(s_1)) D_1 \tag{4}$$

$$\Pi_3 = \Pi_1 + \Pi_2, \tag{5}$$

where the cost of the food quality information service of the food processing factory, that of the food retailer, and that of the food quality information service paid for by the food processing factory are $c(s_1) = \eta_1 s_1^2/2$, $c(s_2) = \eta_2 s_2^2/2$, and $c^*(s_1) = \eta_2 s_1^2/2$, respectively.

2.4. Bertrand Game Pricing Decisions in the Food Supply Chain. The Bertrand game model conditions apply. First, there is competition between enterprises, and at the same time, the enterprises make pricing decisions. In the market, no other enterprises have entered the competition. The Bertrand game occurs without the enterprises knowing the decision behaviors of the other players, and all of the parties set their own prices to maximize profits.

The food processing factory and the retailer are of similar strength, and the parties use the decentralized decision making of the Bertrand game to maximize their own profits as the goal. The approach to solving the model is consistent with the literature [32]. The order of the Bertrand game is as follows: in the first stage, the food processing factory, to maximize its own profit, sets the online channel price; in the second stage, the food retailer, given the unknown online channel price, sets the offline channel sales price to maximize its own profit.

Referring to (3)–(5), we can construct the objective function as follows:

$$\begin{aligned} \max \Pi_1 (p_1, p_2) &= (p_1 - c - c(s_1)) D_1 + (w - c) D_2 \\ \max \Pi_2 (p_1, p_2) &= (p_2 - w - c(s_2)) D_2 \\ &\quad + (c(s_1) - c^*(s_1)) D_2. \end{aligned} \tag{6}$$

Proposition 5. *Under decentralized decision making in the food supply chain, one can solve the optimal food sales prices in the online channel and the offline channel according to the Bertrand game method. Thus, the optimal food sales prices in the online channel and the offline channel are as follows in (9):*

Let

$$\frac{\partial \Pi_1}{\partial p_1} = a_1 + \alpha_2 s_1 - (c - w - p_2)\beta_1 + (s_1 - s_2)\beta_2 + (\alpha_1 + \beta_1)\left(\frac{\eta_1 s_1^2}{2} + c - 2p_1\right) = 0. \tag{7}$$

Let

$$\frac{\partial \Pi_2}{\partial p_2} = a_2 + \alpha_2 s_2 + \beta_1\left(p_1 + \frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2}\right) - \beta_2(s_1 - s_2) + (\alpha_1 + \beta_1)\left(\frac{\eta_2 s_2^2}{2} - 2p_2 + w\right) = 0. \tag{8}$$

We can obtain

$$p_1^1 = \frac{C_1 s_1^2 + C_2 s_1 + C_3 s_2^2 + C_4 s_2 + C_5}{2(4\alpha_1^2 + 3\beta_1^2 + 8\alpha_1\beta_1)}$$
$$p_2^1 = \frac{D_1 s_1^2 + D_2 s_1 + D_3 s_2^2 + D_4 s_2 + D_5}{2(4\alpha_1^2 + 3\beta_1^2 + 8\alpha_1\beta_1)}, \tag{9}$$

where

$$\begin{aligned}
C_1 &= 2\alpha_1^2\eta_1 + 3\beta_1^2\eta_1 + 4\alpha_1\beta_1\eta_1 - \beta_1^2\eta_2 \\
C_2 &= 4\alpha_1\alpha_2 + 4\beta_2\alpha_1 + 4\beta_1\alpha_2 + 2\beta_1\beta_2 \\
C_3 &= \alpha_1\beta_1\eta_2 + \beta_1^2\eta_2 \\
C_4 &= 2\alpha_2\beta_1 - 4\alpha_1\beta_2 - 2\beta_1\beta_2 \\
C_5 &= 2\beta_1 a_2 + 4\beta_1 a_1 + 4a_1\alpha_1 + 4\alpha_1^2 c + 4\alpha_1\beta_1 c + 6\alpha_1\beta_1 w + 6\beta_1^2 w \\
D_1 &= 3\alpha_1\beta_1\eta_1 - 2\alpha_1\beta_1\eta_2 + 3\beta_1^2\eta_1 - 2\beta_1^2\eta_2 \\
D_2 &= -4\alpha_1\beta_2^2 + 2\alpha_2\beta_1 - 2\beta_1\beta_2 \\
D_3 &= 2\alpha_1^2\eta_2 + 4\alpha_1\beta_1\eta_2 + 2\beta_1^2\eta_2 \\
D_4 &= 4\alpha_1\beta_2 + 4\alpha_1\alpha_2 + 4\beta_1\alpha_2 + 2\beta_1\beta_2 \\
D_5 &= 2\beta_1 a_1 + 4\alpha_1 a_2 + 4\beta_1 a_2 + 4w\alpha_1^2 + 2c\alpha_1\beta_1 + 6w\beta_1^2 + 8w\alpha_1\beta_1.
\end{aligned} \tag{10}$$

Furthermore, substituting (9) into (3)–(5), we derive the food processing factory's optimal profit, and the retailer's and total food supply chain's profits under the Bertrand game are as follows:

$$\Pi_1^1 = \left(p_1^1 - c - \frac{\eta_1 s_1^2}{2}\right)D_1^1 + (w - c)D_2^1 \tag{11}$$

$$\Pi_2^1 = \left(p_1^2 - w - \frac{\eta_2 s_2^2}{2}\right)D_2^1 + \left(\frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2}\right)D_1^1 \tag{12}$$

$$\Pi_3^1 = \left(p_1^1 - c - c^*(s_1)\right)D_1^1 + \left(p_2^1 - c - c(s_2)\right)D_2^1. \tag{13}$$

Inference 6. In the food supply chain under the O2O mode, the price is positively correlated with the food quality information service level of the channel.

$$\frac{\partial p_1^1}{\partial s_1} = \frac{(8\alpha_1\beta_1 + 4\alpha_1^2 + 6\beta_1^2)s_1\eta_1 + 2\beta_1\beta_2 - 2\beta_1^2 s_1\eta_2 + 4\alpha_1\alpha_2 + 4\alpha_1\beta_2 + 4\alpha_2\beta_1}{6\beta_1^2 + 8\alpha_1^2 + 16\alpha_1\beta_1} > 0$$
$$\frac{\partial p_2^1}{\partial s_2} = \frac{(4\alpha_1^2 + 4\beta_1^2)s_1\eta_1 + 2\beta_1\beta_2 + 8\alpha_1\beta_1\eta_1 s_2 + 4\alpha_1\alpha_2 + 4\alpha_1\beta_2 + 4\alpha_2\beta_1}{6\beta_1^2 + 8\alpha_1^2 + 16\alpha_1\beta_1} > 0. \tag{14}$$

Inference 7. In the food supply chain under the O2O mode, the food quality information service level at one channel's price is greater than that of another channel.

$$\frac{\partial P_1^1}{\partial s_1} - \frac{\partial P_2^1}{\partial s_1} = \frac{(\beta_1\eta_2 + \alpha_1\eta_1)s_1 + \alpha_2 + 2\beta_2}{2\alpha_1 + 3\beta_1} > 0$$
$$\frac{\partial P_1^1}{\partial s_2} - \frac{\partial P_2^1}{\partial s_2} = \frac{-(\beta_1\eta_2 + \alpha_1\eta_1)s_1 - \alpha_2 - 2\beta_2}{2\alpha_1 + 3\beta_1} < 0. \tag{15}$$

From the above theoretical derivation, we conclude by theoretical analysis that, in the food supply chain under the Bertrand game, the price is positively correlated with the food quality information service level of the food processing factory's or the food retailer's own channel. When the food quality information service level provided by the food retailer is certain, the price in the online channel is higher than that in the offline channel when the food quality information service level is provided by the food processing factory. In contrast, when the food quality information service level provided by the food processing factory is certain, the price in the offline channel is higher than that in the online channel when the food quality information service level is provided by the food retailer. The specific conclusions are verified by the following numerical simulation.

2.5. Stackelberg Game Pricing Decisions in the Food Supply Chain. In the Stackelberg game model for a leader and a follower, the food supply chain in the O2O mode is shown in Figure 1; dominated by the food processing factory, the parties adopt the Stackelberg game under decentralized decision making, and both parties' goal is to maximize their own profits. The Stackelberg game has a reverse order solution. We analyzed the Stackelberg game dominated by the food processing factory. In the first stage, the food processing factory determines the wholesale price to maximize its profits. In the second stage, the food retailer, based the wholesale price determined by the food processing factory's pricing decision, formulates the offline channel price to maximize its own profits.

Referring to (3)–(5), we can construct the objective function as follows:

$$\max \Pi_2 (p_1, p_2) = (p_2 - w - c(s_2)) D_2 + (c(s_1) - c^*(s_1)) D_1 \quad (16)$$
$$\max \Pi_1 (p_1, p_2) = (p_1 - c - c(s_1)) D_1 + (w - c) D_2.$$

Proposition 8. *The food supply chain is shown in Figure 1. According to the Stackelberg method, the optimal food sales prices in the online and the offline channels are*

$$p_1^2 = \frac{E_1 s_1^2 + E_2 s_1 + E_3 s_2^2 + E_4 s_2 + E_5}{4(2\alpha_1^2 + 4\alpha_1\beta_1 + \beta_1^2)} \quad (17)$$

$$p_2^2 = \frac{F_1 s_1^2 + F_2 s_1 + F_3 s_2^2 + F_4 s_2 + F_5 + F_6}{8(2\alpha_1^2 + 4\alpha_1\beta_1 + \beta_1^2)(\alpha_1 + \beta_1)} \quad (18)$$

$$\begin{aligned}
E_1 &= 2\alpha_1^2\eta_1 + 2\beta_1^2\eta_1 + 4\alpha_1\beta_1\eta_1 - \beta_1^2\eta_2 \\
E_2 &= 4\alpha_1\alpha_2 + 4\beta_2\alpha_1 + 4\beta_1\alpha_2 + 2\beta_1\beta_2 \\
E_3 &= \alpha_1\beta_1\eta_2 + \beta_1^2\eta_2 \\
E_4 &= 2\alpha_2\beta_1 - 4\alpha_1\beta_2 - 2\beta_1\beta_2 \\
E_5 &= 4\alpha_1 a_1 + 4\beta_1 a_1 + 4\alpha_1^2 c + 6c\alpha_1\beta_1 + 2\beta_1 a_2 \\
&\quad + 4w\alpha_1\beta_1 + 4\beta_1^2 w \\
F_1 &= 2\beta_1^2\alpha_1\eta_1 - 8\beta_1^2\alpha_1\eta_2 + 6\alpha_1^2\beta_1\eta_1 - 4\alpha_1^2\beta_1\eta_2 \\
&\quad + 4\beta_1^3\eta_1 - 3\beta_1^3\eta_2 \\
F_2 &= 4\alpha_2\beta_1^2 - 12\alpha_1\beta_1\beta_2 - 2\beta_1^2\beta_2 - 8\alpha_1^2\beta_2 + 4\beta_1\alpha_1\alpha_2 \\
F_3 &= 12\alpha_1^2\beta_1\eta_2 + 3\beta_1^3\eta_2 + 4\alpha_1^3\eta_2 + 11\alpha_1\beta_1^2\eta_2 \\
F_4 &= 2\beta_1^2\beta_2 + 8\alpha_1^2\alpha_2 + 16\alpha_1\alpha_2\beta_1 + 6\beta_1^2\alpha_2 + 12\alpha_1\beta_1\beta_2 \\
&\quad + 8\alpha_1^2\beta_2 \\
F_5 &= 24\alpha_1^2\beta_1 w + 6c\alpha_1\beta_1^2 + 16\alpha_1\beta_1 a_2 + 24w\alpha_1\beta_1^2 \\
&\quad + 8w\beta_1^3 \\
F_6 &= 4c\alpha_1^2\beta_1 + 8w\alpha_1^3 + 8a_2\alpha_1^2 + 4\alpha_1\beta_1 a_1 + 8\beta_1^2 a_1 \\
&\quad + 6\beta_1^2 a_2.
\end{aligned} \quad (19)$$

The reverse induction method is used to solve the model. Based on the sales price in the online channel, the food retailer determines the price in the offline channel to maximize its own profit. Based on the price in the offline channel, the food processing factory sets the price in the online channel to maximize its own profit.

Let

$$\frac{\partial \Pi_2}{\partial p_2} = a_2 + \alpha_2 s_2 + \beta_1 \left(p_1 + \frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2} \right) - \beta_2 (s_1 - s_2) + (\alpha_1 + \beta_1) \left(\frac{\eta_2 s_2^2}{2} - 2p_2 + w \right) = 0 \quad (20)$$

$$p_2^S = \frac{a_2 + \beta_1 P_1 + \alpha_2 s_2 - \beta_2 (s_1 - s_2) + \beta_1 \left((\eta_1 s_2^2/2) - (\eta_2 s_2^2/2) \right) + (\alpha_1 + \beta_1) \left((\eta_2 s_2^2/2) + w \right)}{2\alpha_1 + 2\beta_1}. \quad (21)$$

Substituting (21) into (3) and substituting the response into the derivative of its profit on the price,

$$\begin{aligned}
\frac{\partial \Pi_1}{\partial p_1} &= a_1 + \frac{3\alpha_1 - \beta_1}{2} p_1 + \alpha_2 s_1 \\
&\quad + \frac{\beta_2 (2\alpha_1 + \beta_1)}{2(\alpha_1 + \beta_1)} (s_1 - s_2) \\
&\quad + \frac{\alpha_1 (\alpha_1 + 2\beta_1)}{2(\alpha_1 + \beta_1)} \left(\frac{\eta_1 s_1^2}{2} + c \right) + \frac{\beta_1 s_2^2 \eta_2}{4} \\
&\quad + \frac{\beta_1 a_2 + \beta_1 \alpha_2 s_2 + \beta_1^2 \left((\eta_1 s_1^2/2) - (\eta_2 s_1^2/2) \right)}{2(\alpha_1 + \beta_1)} \\
&\quad + \beta_1 w - \frac{\beta_1 c}{2} = 0.
\end{aligned} \quad (22)$$

Furthermore, we derive the food processing factory's optimal price.

The Stackelberg game method is used to solve the optimal food sales price in the online and offline channels. According to the demand function, we obtain the demand and the optimal wholesale price.

$$w^2 = \frac{J_1 s_1^2 + J_2 s_1 + J_3 s_2^2 + J_4 s_2 + J_5}{4(\alpha_1^3 + 12\alpha_1^2\beta_1 + 8\alpha_1\beta_1^2)} \quad (23)$$

$$J_1 = 2\alpha_1\beta_1^2\eta_2 - 2\alpha_1\beta_1^2\eta_1 - 2\alpha_1^2\beta_1\eta_1 + \alpha_1^2\beta_1\eta_2$$

$$J_2 = 2\alpha_1\alpha_2\beta_1 + 2\alpha_2\beta_1^2 - 2\alpha_1\beta_1\beta_2 - 2\alpha_1^2\beta_2$$

$$J_3 = -\alpha_1^3\eta_2 - 2\alpha_1\beta_1^2\eta_2 - 3\alpha_1^2\beta_1^2\eta_2$$

$$J_4 = 2\beta_1^2\beta_2 + 2\alpha_2\beta_1^2 + 2\beta_1^2\beta_2 + 4\alpha_1\alpha_2\beta_1 + 2\alpha_1\beta_1\beta_2$$

$$J_5 = 2\alpha_1^2 a_1 + 2\alpha_1^3 c + 2\beta_1^2 a_1 + 2\beta_1^2 a_2 + 4\alpha_1\beta_1^2 c + 6\alpha_1^2\beta_1 c + 2\alpha_1\beta_1 a + 4\alpha_1\beta_1 a_2. \tag{24}$$

Furthermore, we derive the optimal profit of the food processing factory, food retailer, and food supply chain under the Stackelberg game as follows:

$$\Pi_1^2 = \left(p_1^2 - c - \frac{\eta_1 s_1^2}{2}\right)D_1^2 + \left(w_1^2 - c\right)D_2^2 \tag{25}$$

$$\Pi_2^2 = \left(p_2^2 - w_2^2 - \frac{\eta_2 s_2^2}{2}\right)D_2^2 + \left(\frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2}\right)D_1^2 \tag{26}$$

$$\Pi_3^2 = \left(p_1^2 - c - c^*\left(s_1\right)\right)D_1^2 + \left(p_2^2 - c - c\left(s_2\right)\right)D_2^2. \tag{27}$$

Inference 9. According to the food supply chain under the O2O mode, the price is positively correlated with the food quality information service level of the food processing factory's or the food retailer's channel.

$$\begin{aligned}\frac{\partial P_1^2}{\partial s_1} &= \frac{\left(8\alpha_1\beta_1\eta_1 + 4\beta_1^2\eta_1 + 4\alpha_1^2\eta_1 - 2\beta_1^2\eta_2\right)s_1 + 4\alpha_1\alpha_2 + 4\alpha_2\beta_1 + 4\alpha_1\beta_2 + 2\beta_1\beta_2}{2\left(\alpha_1^2 + 4\alpha_1\beta_1 + \beta_1^2\right)} > 0\\ \frac{\partial P_2^2}{\partial s_2} &= \frac{\left(24\alpha_1^2\beta_1 + 22\alpha_1\beta_1^2 + 6\beta_1^3 + 8\alpha_1^3\right)\eta_2 s_2 + 8\alpha_1^2\alpha_2 + 8\alpha_1^2\beta_2 + 16\beta_1\alpha_1\alpha_2 + 12\alpha_1\beta_1\beta_2 + 6\alpha_2\beta_1^2 + 2\beta_1^2\beta_2}{2\left(\alpha_1^2 + 4\alpha_1\beta_1 + \beta_1^2\right)} > 0.\end{aligned} \tag{28}$$

Inference 10. According to the food supply chain under the O2O mode, the food quality information service level at one channel's price is greater than that of another channel.

$$\begin{aligned}&\frac{\partial P_1^2}{\partial s_1} - \frac{\partial P_2^2}{\partial s_1}\\ &= \frac{\left(6\alpha_1\beta_1^2\eta_2 + 6\alpha_1^2\beta_1\eta_1 + 4\alpha_1^2\beta_1\eta_2 + \eta_2\beta_1^3 + 4\alpha_1^3\eta_1\right)s_1 + \left(8\beta_2 + 4\alpha_2\right)\alpha_1^2 + \left(12\beta_2 + 6\alpha_2\right)\beta_1\alpha_1 + 3\beta_2\beta_1^2 + 2\beta_1^2\alpha_2}{2\alpha_1 + 3\beta_1} > 0\\ &\frac{\partial P_1^2}{\partial s_2} - \frac{\partial P_2^2}{\partial s_2} = \frac{\left(-10\alpha_1^2\beta_1 + 7\alpha_1\beta_1^2 + \beta_1^3 + 4\alpha_1^3\right)\eta_2 s_1 - \left(4\alpha_2 + 8\beta_2\right)\alpha_1^2 - \left(6\alpha_1 + 12\beta_2\right)\beta_1\alpha_1 - 3\beta_2\beta_1^2 - \beta_1^2\alpha_2}{2\alpha_1 + 3\beta_1} < 0.\end{aligned} \tag{29}$$

We conclude through theoretical analysis that in the food supply chain under the Stackelberg game, the price is positively correlated with the food quality information service level of the food processing factory's or the food retailer's own channel. Therefore, the food processing factory and food retailer should reasonably optimize the network layout of the offline channel and continuously improve the food quality information service level, which involves optimizing the functions of different types of offline channels and improving the control level of the food quality information.

2.6. Centralized Pricing Decisions in the Food Supply Chain. The food supply chain under centralized pricing decisions (that is, the food processing factory and the retailer) aims to maximize the total supply of the food supply chain.

Referring to (3)–(5), we can construct the objective function as follows:

$$\begin{aligned}\max\Pi_{P_1} &= \left(p_1 - c - c^*\left(s_1\right)\right)D_1\\ &\quad + \left(p_2 - c - c\left(s_2\right)\right)D_2\\ \max\Pi_{P_2} &= \left(p_1 - c - c^*\left(s_1\right)\right)D_1\\ &\quad + \left(p_2 - c - c\left(s_2\right)\right)D_2.\end{aligned} \tag{30}$$

Let

$$\begin{aligned}\frac{\partial\Pi}{\partial p_1} &= a_1 - \beta_1\left(\frac{\eta_2 s_2^2}{2} - 2p_2\right) + \alpha_2 s_1 + \beta_2\left(s_1 - s_2\right)\\ &\quad + \alpha_1 c + \left(\alpha_1 + \beta_1\right)\left(\frac{\eta_2 s_2^2}{2} - 2p_2\right) = 0\\ \frac{\partial\Pi}{\partial p_2} &= a_2 - \beta_1\left(\frac{\eta_2 s_2^2}{2} - 2p_1\right) + \alpha_2 s_1 + \beta_2\left(s_1 - s_2\right)\\ &\quad + \alpha_1 c + \left(\alpha_1 + \beta_1\right)\left(\frac{\eta_2 s_2^2}{2} - 2p_2\right) = 0.\end{aligned} \tag{31}$$

$H = \begin{bmatrix} -2b_1-2\beta_1 & 2\beta_1 \\ 2\beta_1 & -2b_1-2\beta_1 \end{bmatrix}$, as of $|H| = 4\alpha_1^2 + 8\alpha_1\beta_1 > 0$, and the first-order master $-2b_1 - 2\beta_1 < 0$, so the total profit function of the food supply chain is the concave function for p_1 and p_2. Joining the above first-order partial derivatives and solving the equation, we obtain the optimal price in the online and offline channels under centralized decision making.

Proposition 11. *Under centralized decision making in the food supply chain, the food supply chain's profit can be maximized. In this case, the pricing decision is the global optimum. Thus, the optimal food sales price in the online channel and offline channel are*

$$p_1^3 = \frac{(\alpha_1 + 2\beta_1)\alpha_1\beta_2 s_1^2 + 2(\alpha_1\alpha_2 + \alpha_1\beta_2 + \alpha_2\beta_1)s_1 + 2(\alpha_2\beta_1 - \alpha_1\beta_2)s_2 + G_1}{4\alpha_1^2 + 8\alpha_1\beta_1} \quad (32)$$

$$p_2^3 = \frac{(\alpha_1 + 2\beta_1)\alpha_1\beta_2 s_2^2 + 2(\alpha_1\alpha_2 + \alpha_1\beta_2 + \alpha_2\beta_1)s_2 + 2(\alpha_2\beta_1 - \alpha_1\beta_2)s_1 + G_2}{4\alpha_1^2 + 8\alpha_1\beta_1}, \quad (33)$$

where

$$\begin{aligned} G_1 &= 2(\alpha_1 + \beta_1)a_1 + 2\beta_1 a_2 + 2(\alpha_1 + 2\beta_1)\alpha_1 c \\ G_2 &= 2(\alpha_1 + \beta_1)a_2 + 2\beta_1 a_1 + 2(\alpha_1 + 2\beta_1)\alpha_1 c. \end{aligned} \quad (34)$$

Furthermore, we derive the optimal profits of the food processing factory, retailer, and the total food supply chain under centralized decision making:

$$\Pi_1^3 = \left(p_1^3 - c - \frac{\eta_1 s_1^2}{2}\right)D_1^3 + (w - c)D_2^3 \quad (35)$$

$$\Pi_2^3 = \left(p_2^3 - w - \frac{\eta_2 s_2^2}{2}\right)D_2^3 + \left(\frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2}\right)D_1^3 \quad (36)$$

$$\Pi_3^3 = \left(p_1^3 - c - c^*(s_1)\right)D_1^3 + \left(p_2^3 - c - c(s_2)\right)D_2^3. \quad (37)$$

Inference 12. Based on the food supply chain under the O2O mode, the price is positively correlated with the food quality information service level of the food processing factory's or the food retailer's channel.

$$\begin{aligned} \frac{\partial P_1^3}{\partial s_1} &= \frac{(\alpha_1 + 2\beta_1)\alpha_1\eta_2 + \alpha_1\alpha_2 + \alpha_1\beta_2 + \alpha_2\beta_1}{2\alpha_1(\alpha_1 + 2\beta_1)} > 0 \\ \frac{\partial P_2^3}{\partial s_2} &= \frac{(\alpha_1 + 2\beta_1)\alpha_1\eta_2 + \alpha_1\alpha_2 + \alpha_1\beta_2 + \alpha_2\beta_1}{2\alpha_1(\alpha_1 + 2\beta_1)} > 0. \end{aligned} \quad (38)$$

Inference 13. With the food supply chain under the O2O mode, the food quality information service level at the food processing factory's or the food retailer's own channel price is greater than that of another channel.

$$\begin{aligned} \frac{\partial P_1^3}{\partial s_1} - \frac{\partial P_2^3}{\partial s_1} &= \frac{(\beta_1\eta_2 + \alpha_1\eta_1)s_1 + \alpha_2 + 2\beta_2}{2\alpha_1 + 3\beta_1} > 0 \\ \frac{\partial P_1^3}{\partial s_2} - \frac{\partial P_2^3}{\partial s_2} &= \frac{-(\beta_1\eta_2 + \alpha_1\eta_1)s_1 - \alpha_2 - 2\beta_2}{2\alpha_1 + 3\beta_1} < 0. \end{aligned} \quad (39)$$

We conclude through theoretical analysis that in the food supply chain under centralized decision making, the price is positively correlated with the food quality information service level of the food processing factory's or the food retailer's own channel.

The conclusions can be summarized as follows. Under centralized and decentralized decision making, the online channel price of the food processing factory is positively correlated with the food quality information service level of its own channel, and the same is true for the food retailer. The results show that as the food processing factory improves the level of its food quality information service, the costs of that service will increase. Thus, the food processing factory will need to increase the sales price to compensate for the service cost, whereas the food retailer can take the opportunity to increase its price.

The food quality information service level of the food processing factory has a greater impact on the price in its own channel than on the price in the food retailer's offline channel. The same is true for the food retailer. The results show that when the level of the offline channel's food quality information service is reduced, the price in the online channel decreases. The food retailer adopts the decision to reduce the price. However, when the retailer improves the food quality information service level, the price in the offline channel increases. The food processing factory adopts the decision to increase the price.

2.7. Quantity Discount Coordination Mechanism in the Food Supply Chain. To study a food supply chain that is in effective and continuous operation with high efficiency (reasonable cost), high credit, and high quality, we choose a supply chain with the following attributes. First, based on the previously discussed conclusions, we study a food processing factory that sets its wholesale prices based on the number of wholesale products for food retailers [33]. Second, we optimize the execution of a long-term discount contract that benefits the main body of the food supply chain and maximizes its profits. Additionally, we coordinate the range of parameters to benefit the distribution between the food processing factory and food retailers. Thus, we build a food supply chain with a quantitative discount coordination mechanism.

We can establish the quantity discount mechanism of the food supply chain as follows:

$$w(k) = w - kD, \tag{40}$$

where w is the optimal value of the wholesale price of the food, D is the demand, and k is the quantity discount coefficient. The decision order is the same as with the Stackelberg game. We establish the profit objective function of the food retailer as

$$\begin{aligned}\Pi_2 &= \left(p_2 - w(D_2) - \frac{\eta_2 s_2^2}{2}\right) D_2 + \left(\frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2}\right) D_1 \\ \Pi_2 &= \left(p_2 - w - \frac{\eta_2 s_2^2}{2}\right)[a_2 - \alpha_1 p_2 + \alpha_2 s_2 \\ &\quad + \beta_1 (p_1 - p_2) + \beta_2 (s_2 - s_1)] + k [a_2 - \alpha_1 p_2 \\ &\quad + \alpha_2 s_2 + \beta_1 (p_1 - p_2) + \beta_2 (s_2 - s_1)]^2 + \left(\frac{\eta_1 s_1^2}{2} \right. \\ &\quad \left. - \frac{\eta_2 s_1^2}{2}\right)[a_1 - \alpha_1 p_1 + \alpha_2 s_1 + \beta_1 (p_2 - p_1) \\ &\quad + \beta_2 (s_1 - s_2)].\end{aligned} \tag{41}$$

Let

$$\begin{aligned}\frac{\partial \Pi_2}{\partial p_2} &= \left(p_2 - w - \frac{\eta_2 s_2^2}{2}\right)(-\alpha_1 - \beta_1) \\ &\quad + (2k(-\alpha_1 - \beta_1) + 1) \\ &\quad \cdot [a_2 - \alpha_1 p_2 + \alpha_2 s_2 + \beta_1 (p_1 - p_2) + \beta_2 (s_2 - s_1)] \\ &\quad + \beta_1 \left(\frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2}\right) = 0.\end{aligned} \tag{42}$$

We obtain the reaction function of the food retailer as

$$p_2(p_1) = \frac{[a_2 + (\alpha_1 + \beta_1)(\eta_2 s_2^2/2) + w] + \beta_1 P_1 + \alpha_2 s_2 + \alpha_1((\eta_1 s_1^2/2) - (\eta_2 s_1^2/2)) - \beta_2 (s_1 - s_2) - 2k(\alpha_1 + \beta_1)[a_2 + \beta_1 P_1 + \alpha_2 s_2 + \beta_2 (s_2 - s_1)]}{2\alpha_1 + 2\beta_1 - 2k(\alpha_1 + \beta_1)^2}. \tag{43}$$

Then, by substituting $p_2(p_1)$ into (1), we obtain the demand D_1^{QD}, D_2^{QD}.

The food processing factory optimizes the profits of the food supply chain based on the response of the food retailer.

$$\begin{aligned}\Pi_3^{QD} &= \left(p_1^{QD} - c - \frac{\eta_2 s_1^2}{2}\right) D_1^{QD} \\ &\quad + \left(p_2^{QD} - c - \frac{\eta_2 s_2^2}{2}\right) D_2^{QD}.\end{aligned} \tag{44}$$

Substituting p_2^{QD}, D_1^{QD}, D_2^{QD} into Π_3^{QD}, let $\Pi_3^{QD}/w = 0$, $\Pi_3^{QD}/k = 0$, $\Pi_3^{QD}/P_1 = 0$:

$$p_1^{QD} = \frac{(\alpha_1 + 2\beta_1)\alpha_1 \eta_2 s_1^2 + w + 2(\alpha_1\alpha_2 + \alpha_1\beta_2 + \alpha_2\beta_1) s_1 + 2(\alpha_2\beta_1 - \alpha_1\beta_2) s_2 + 2(\alpha_1 + \beta_1) a_1 + 2\beta_1 a_2 + 2(\alpha_1 + 2\beta_1)\alpha_1 c}{4\alpha_1(\alpha_1 + 2\beta_1)} \tag{45}$$

$$p_2(p_1) = \frac{[a_2 + (\alpha_1 + \beta_1)(\eta_2 s_2^2/2) + w] + \beta_1 P_1 + \alpha_2 s_2 + \alpha_1((\eta_1 s_1^2/2) - (\eta_2 s_1^2/2)) - \beta_2 (s_1 - s_2) - 2k(\alpha_1 + \beta_1)[a_2 + \beta_1 P_1 + \alpha_2 s_2 + \beta_2 (s_2 - s_1)]}{2\alpha_1 + 2\beta_1 - 2k(\alpha_1 + \beta_1)^2}. \tag{46}$$

We obtain the optimal wholesale price:

$$\begin{aligned}w^{QD} &= \frac{I_1 s_1^2 + I_2 s_1 + I_3 s_2 + I_4}{4(\alpha_1^3 + 3\alpha_1^2\beta_1^2 + 2\alpha_1\beta_1^2)} \\ &\quad + k\frac{I_5 s_1^2 + I_6 s_1 + I_7 s_2^2 + I_8 s_2 + I_9}{4\alpha_1(\alpha_1^2 + 3\alpha_1\beta_1 + 2\beta_1^2)}\end{aligned}$$

$$I_1 = 2\alpha_1\beta_1^2\eta_2 - 2\alpha_1\beta_1^2\eta_1 - 4\alpha_1\beta_1^2\eta_1 + \alpha_1^2\beta_1^2\eta_2$$

$$I_2 = 2\alpha_1\alpha_2\beta_1 + 2\alpha_2\beta_1^2 + 2\alpha_1\beta_1\beta_2$$

$$I_3 = -2\alpha_1\beta_1\beta_2 + 2\alpha_2\beta_1^2$$

$$\begin{aligned}I_4 &= 4\alpha_1\beta_1^2 c + 2\alpha_1\beta_1 a_1 + 2\beta_1^2 a_1 + 2\beta_1^2 a_2 \\ &\quad + 10\alpha_1^2\beta_1 c + 4c\alpha_1^3\end{aligned}$$

$$I_5 = -4\alpha_1\beta_1^3\eta_2 - 6\alpha_1^2\beta_1^2\eta_2 - 2\alpha_1^3\beta_1\eta_2$$

$$I_6 = 8\alpha_1\beta_1^2\beta_2 + 12\alpha_1^2\beta_1\beta_2 + 4\alpha_1^3\beta_2$$

$$I_7 = 4\alpha_1\beta_1^3\eta_2 + 10\alpha_1^2\beta_1^2\eta_2 + 8\alpha_1^3\beta_1\eta_2 + 2\alpha_1^4\eta_2$$

$$\begin{aligned}I_8 &= -8\alpha_1\beta_1^2\beta_2 + 12\alpha_1^2\beta_1\beta_2 - 8\alpha_1\alpha_2\beta_1^2 - 12\alpha_1^2\alpha_2\beta_1 \\ &\quad - 4\alpha_1^3\alpha_2 - 4\alpha_1^3\beta_2\end{aligned}$$

$$I_9 = -8\alpha_1\beta_1^2 a_2 + 8\alpha_1^2\beta_1^2 c + 12\alpha_1^3\beta_1 c + 12\alpha_1^2\beta_1 a_2 + 4\alpha_1^4 c - 4\alpha_1^3 a_2. \quad (47)$$

Substituting p_1^{QD}, w into p_2, we obtain

$$p_2^{QD} = \frac{(\alpha_1 + 2\beta_1)\alpha_1\eta_2 s_2^2 + 2(\alpha_1\alpha_2 + \alpha_1\beta_2 + \alpha_2\beta_1)s_2 + 2(\alpha_2\beta_1 - \alpha_1\beta_2)s_1 + 2(\alpha_1 + \beta_1)a_2 + 2\beta_1 a_1 + 2(\alpha_1 + 2\beta_1)\alpha_1 c}{4\alpha_1(\alpha_1 + 2\beta_1)}. \quad (48)$$

At this time, $p_2^{QD} = p_2^C$. The optimal pricing of the food processing factory under the Stackelberg game is equal to the optimal price under centralized decision making. In other words, the quantitative discount mechanism enables the coordination of the food supply chain.

Proposition 14. *The food supply chain is shown in Figure 1. According to the Stackelberg game method, we analyzed the Stackelberg game dominated by the food processing factory. Thus, the profits of the food processing factory and food retailer under the Stackelberg game are*

$$\Pi_1^2 = \left(p_1^2 - c - \frac{\eta_1 s_1^2}{2}\right)D_1^2 + \left(w_1^2 - c\right)D_2^2 \quad (49)$$

$$\Pi_2^2 = \left(p_2^2 - w_2^2 - \frac{\eta_2 s_2^2}{2}\right)D_2^2 + \left(\frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2}\right)D_1^2. \quad (50)$$

After coordinating the food processing factory and food retailer, the profits are as follows:

$$\begin{aligned}\Pi_1^{QD} &= \left(p_1^{QD} - c - \frac{\eta_1 s_1^2}{2}\right)D_1^{QD} + \left[\left(w_1^{QD} - kD_2^{QD}\right) - c\right]D_2^{QD} \\ \Pi_2^{QD} &= \left[p_2^{QD} - \left(w_2^{QD} - kD_2^{QD}\right) - \frac{\eta_2 s_2^2}{2}\right]D_2^{QD} + \left(\frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2}\right)D_1^{QD}.\end{aligned} \quad (51)$$

3. Results and Discussion

Nianyugou Wangu Processing Co., Ltd., uses its own retail channel and brand, and its downstream retailer provides a variety of support services. With this system, the relationships between the supply chain partners are more stable, and a win-win effect is achieved. Therefore, we combined the success stories involving Nianyugou Wangu Processing Co., Ltd., and we make recommendations for food processing factory management.

For the parameter selection, we draw on the literature, such as Garnett et al. and Bin et al., and we analyze the actual food supply chain situation, the basic parameter values of which are given as follows:

$$\begin{aligned} a_1 &= 210, \\ a_2 &= 240, \\ c &= 4, \\ w &= 10, \\ \beta_1 &= 2, \\ \beta_2 &= 1, \\ \alpha_1 &= 4, \\ \alpha_2 &= 2, \\ \eta_1 &= 7, \\ \eta_2 &= 2. \end{aligned} \quad (52)$$

With the above theoretical deduction formula, we analyze the impact of the food quality information service level on the food processing factory's and retailer's pricing decisions under a different decision regime.

3.1. The Impact of the Level of the Online Channel's Food Quality Information Service on Price. According to (9), (17)-(18), and (32)-(33), we use $s_2 = 6$, $s_1 \in [0, 10]$, and the results are shown in Table 1. Then, Matlab software is used to graph the results (see Figure 3). We analyze the impact of the level of the online channel's food quality information service on price as follows.

As shown in Figure 3, with improvements in the food quality information service level in the online channel, the sales prices in the online channel and the offline channel will increase. Research by Bin et al. and Chen et al. concluded that the service level is positively correlated with price in the supply chain. However, we consider a very different industry application. This paper establishes the profit function of the food quality information service level under the O2O mode. We analyze the food quality information service in a food supply chain consisting of a food processing factory and a food retailer. We have verified the conclusion that the food quality information service level is positively correlated with the price. Under the Stackelberg and Bertrand games, the level of the online channel's food quality information service has a greater impact on the price in its own channel than on the price in the offline channel. Under the Stackelberg game,

Table 1: The impact of the level of the online channel's food quality information service on price.

s_1	0	1	2	3	4	5	6	7	8	9	10
p_1^B	28.2	30.26	36.06	45.6	58.89	75.91	96.69	121.2	149.5	181.5	217.2
P_2^B	49.2	50.01	52.54	56.79	62.74	70.41	79.8	90.9	103.7	118.2	134.5
p_1^S	28.38	31.34	39.59	53.13	71.97	96.1	125.5	160.3	200.3	245.6	296.2
P_2^S	50.26	50.6	51.69	53.53	56.13	59.49	63.6	68.46	74.08	80.46	87.59
p_1^C	29.19	29.94	31.69	34.44	38.19	42.94	48.69	55.44	63.19	71.94	81.69
P_2^C	31.06	31.81	33.56	36.31	40.06	44.81	50.56	57.31	65.06	73.81	87.59

Table 2: The impact of the level of the offline channel's food quality information service on price.

s_2	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
p_1^B	93.86	93.9	94.1	94.5	95.06	95.79	96.69	97.76	99	100.4	102	103.8	106.1	107.8	110.1	112.5
P_2^B	55.2	55.96	57.74	60.56	64.4	69.27	75.17	82.1	90.06	99.04	109.1	120.1	132.2	145.3	159.4	174.6
p_1^S	122.6	122.7	122.9	123.3	123.9	124.6	125.5	126.6	127.9	129.4	131	132.8	134.8	137	139.3	141.8
P_2^S	50.26	50.6	51.69	53.53	56.13	59.49	63.6	68.46	74.08	80.46	87.59	95.47	104.1	113.5	123.7	134.6
p_1^C	48.69	48.69	48.69	48.69	48.69	48.69	48.69	48.69	48.69	48.69	48.69	48.69	48.69	48.69	48.69	48.69
P_2^C	31.06	31.81	33.56	36.31	40.06	44.81	50.56	57.31	65.06	73.81	83.56	94.31	106.1	118.8	132.6	147.3

there is an optimal price for the online channel when the food quality information service level it provides is greater than the critical value of 2, and there is an optimal price for the offline channel when the food quality information service level it provides is less than the critical value of 2. The price difference between the two channels is the largest under the Stackelberg game.

3.2. The Impact of the Level of the Offline Channel's Food Quality Information Service on Price. According to (9), (17)-(18), and (32)-(33), we use $s_1 = 6$, $s_2 \in [0, 15]$, and the results are shown in Table 2. Then, Matlab software is used to graph the results (see Figure 4). We analyze the impact of the level of the offline channel's food quality information service on price as follows.

As shown in Figure 4, with improvements in the food quality information service level of the offline channel, the sales prices of both the online and offline channels increase. Therefore, the food quality information service level is positively correlated with the price of the food processing factory's and the food retailer's own channel. Moreover, the change amplitude of the price for the online channel is greater than that for the offline channel. There is an optimal price for the online channel under the Bertrand game with an improvement in the level of the offline channel's food quality information service. The price in the online channel is higher than that in the offline channel in the case of centralized decision making in which the food quality information service level provided by the offline channel is less than the critical value of 5.4, and there is a small price difference between the two channels. The price in the online channel is lower than that in the offline channel in the case of centralized decision making in which the food quality information service level provided by the offline channel is higher than the critical value of 5.4, while the price difference between the two channels is the largest.

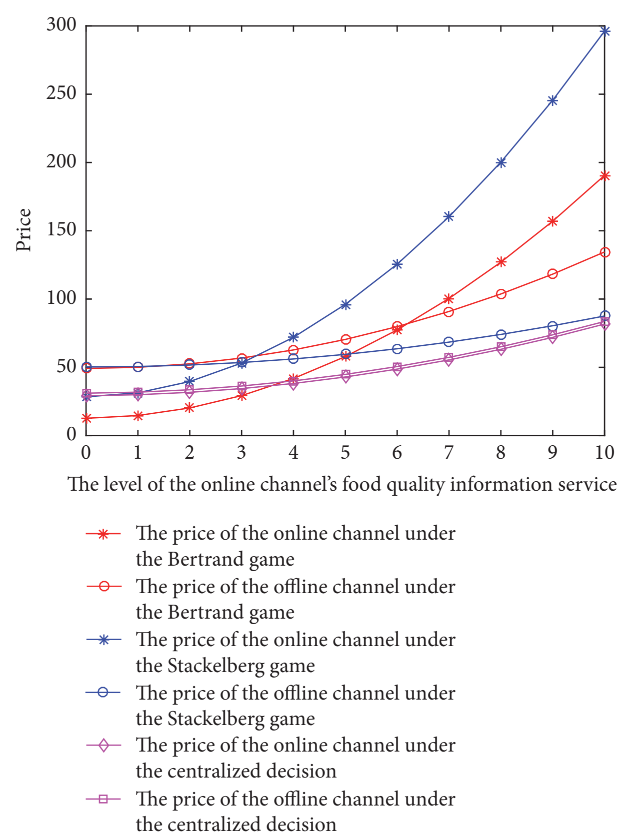

Figure 3: The impact of the level of the online channel's food quality information service on price.

Therefore, if the food processing factory and retailer want to increase their profits, they should continuously improve their level of food quality information service. At the same time, service regulations for food quality information should be adopted. On the one hand, the food retailer should

TABLE 3: The impact of the level of the online channel's food quality information service on the food processing factory's profit.

s_1	0	0.8	1.6	2.4	3.2	4	4.8	5.6	6.4	7.2	8	8.8	9.6
Π_1^B	1802	1562	958	218.7	−274	13.28	1766	5823	14000	25000	42000	67000	100000
Π_1^S	4279	3986	3161	1978	735.6	−141	−98.24	1541	5583	13000	25000	42000	60000
Π_1^C	3851	3543	2545	971.9	−970	−2987	−4697	−5630	−5527	−2841	2265	11000	24000

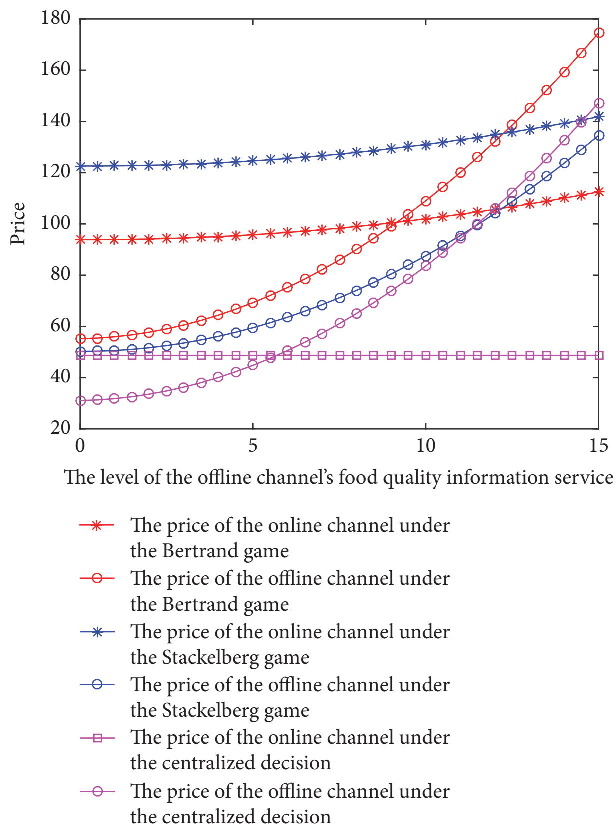

FIGURE 4: The impact of the level of the offline channel's food quality information service on price.

improve the filter level for the food processing factory, including both food quality information and food production information. Through the constraints of the service contract, the level of the food quality information services can be improved. On the other hand, the food processing factory should strengthen its food quality information timeliness, and through its contractual relations, the fairness and validity of the contract under the Bertrand game pricing decision in the food supply chain will improve.

3.3. The Impact of the Level of the Online Channel's Food Quality Information Service on the Food Processing Factory's Profit. According to (11), (25), and (35), we use $s_2 = 6$, $s_1 \in [0, 9.6]$. The results are shown in Table 3. Then, Matlab software is used to graph the results (see Figure 5). We analyze the impact of the level of the online channel's food quality information service on the food processing factory's profit as follows.

As seen from the inflection point in Figure 5, the food processing factory's profit is gradually reduced under the Stackelberg game and the Bertrand game when the level of the online channel's food quality information service is less than the critical value of 3.2. The food processing factory's profit gradually increases under the Stackelberg game and the Bertrand game when the level of the online channel's food quality information service is greater than the critical value of 3.2. However, the food processing factory's profit is gradually reduced under centralized decision making when the level of the online channel's food quality information service is less than the critical value of 5.6. The food processing factory's profit gradually increases under centralized decision making when the level of the online channel's food quality information service is greater than the critical value of 5.6. Compared with the three decision methods, it can be concluded that the profit is optimal when the food processing factory chooses the Stackelberg game. Therefore, it is wise for the food processing factory to compete with the food retailer under the Stackelberg game.

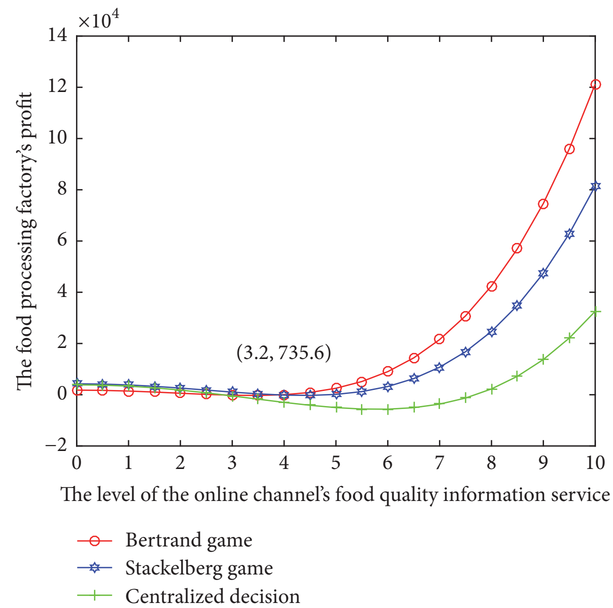

FIGURE 5: The relationship between the level of the online channel's food quality information service and the food processing factory's profit.

3.4. The Impact of the Level of the Online Channel's Food Quality Information Service on the Food Retailer's Profit. According to (12), (26), and (36), we use $s_2 = 6$, $s_1 \in [0, 3.5]$, and then we use Matlab software to graph the results (see Figure 6). We analyze the impact of the level of the online channel's food quality information service on the food retailer's profit as follows.

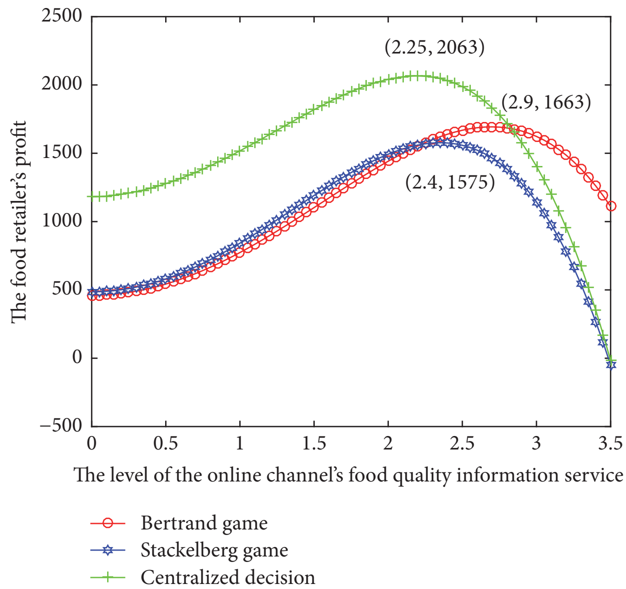

Figure 6: The relationship between the level of the online channel's food quality information service and the food retailer's profit.

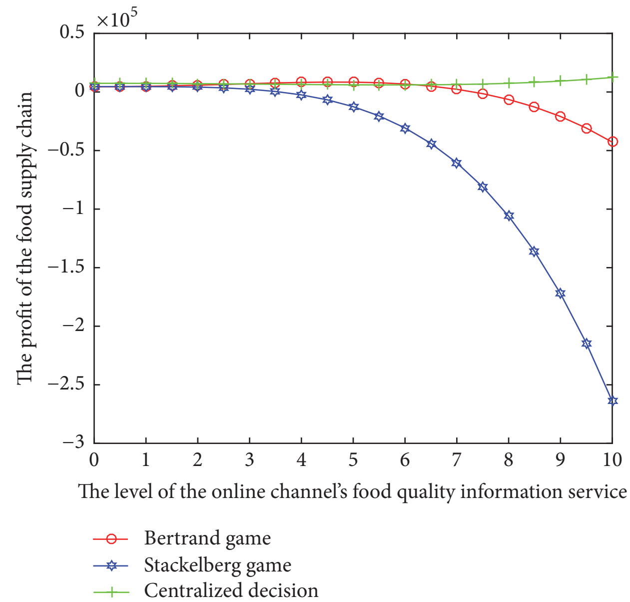

Figure 7: The relationship between the level of the online channel's food quality information service and the profit of the food supply chain.

As shown in Figure 6, the food retailer's profit is gradually reduced under centralized decision making when the level of the online channel's food quality information service reaches the critical value of 2.25. The food retailer's profit is gradually reduced under the Stackelberg game when the level of the online channel's food quality information service achieves the critical value of 2.4. However, the food retailer's profit is gradually reduced under the Bertrand game when the level of the online channel's food quality information service achieves the critical value of 2.9. Improving the level of the online channel's food quality information service exerts pressure on the food retailer. Based on the above analysis, the food retailer should choose the centralized decision making profit to achieve an optimal pricing decision.

3.5. The Impact of the Level of the Online Channel's Food Quality Information Service on the Total Profit of the Food Supply Chain. According to (13), (17), (18), (21), (23), (25), (26), (27), and (37), we use $s_2 = 6$, $s_1 \in [0, 10]$, and then we use Matlab software to graph the results (see Figure 7). We analyze the impact of the level of the online channel's food quality information service on the profit of the food supply chain as follows.

As shown in Figure 7, with improved food quality information service level of the food processing factory under decentralized decision making, the total profit of the food supply chain decreases. However, the total profit of the food supply chain gradually decreases under centralized decision making. Therefore, there is an optimal profit value in the food supply chain under centralized decision making.

In summary, when the food quality information service is provided by the online channel, the online channel's food quality information service level is positively related to the profits of the food processing factory and negatively related to those of the food retailer. At this point, the total profit of the food supply chain also decreases. As a result, the food processing factory chooses the Stackelberg game to make pricing decisions, so the food retailer should choose to make a centralized pricing decision. In other words, the online channel's food quality information service level only brings its profits, and for the retailer and the food supply chain, it is not the best decision.

Therefore, if the food processing factory wants to increase its profits, it should continuously improve the level of the food quality information service provided by the online channel. There are many shortcomings in the food quality information services provided by online channels, such as business fraud related to product information (quality), fictional product sizes, the uploading of fake photos, and other types of poor quality food information provided to consumers.

Therefore, to improve the online channel's food quality information service level in terms of technical aspects, the information in the online channel should be quantified through graded information, and data sharing with food regulatory authorities should occur to provide consumers with adequate information. Regarding delivery, the online channel improves the logistical speed and enhances consumer confidence. In terms of business strategies, we recommend providing additional information in the online food categories, such as increasing the product information for imported food products, differentiating online products from those in the offline channel, and fully discussing the online channel advantages. To improve the online food traceability system, food production and "one-vote pass" distribution should be used to make the source of food quality information traceable, to ensure that quality and safety are controllable and to improve the transparency of food quality information services and thereby increase consumer confidence.

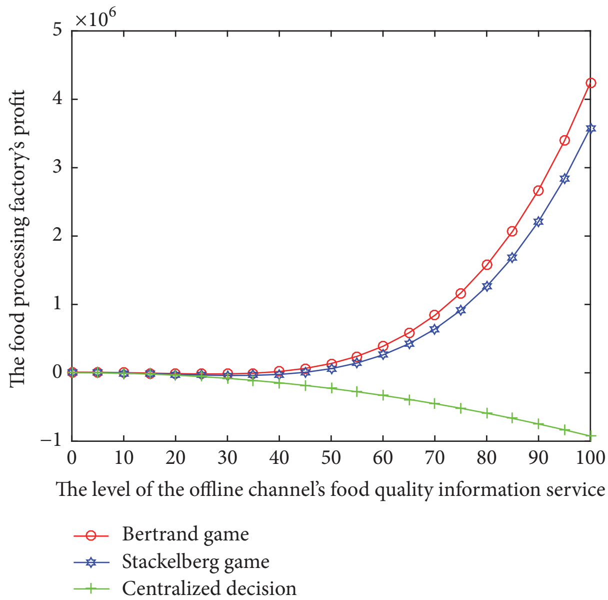

Figure 8: The relationship between the level of the offline channel's food quality information service and the food processing factory's profit.

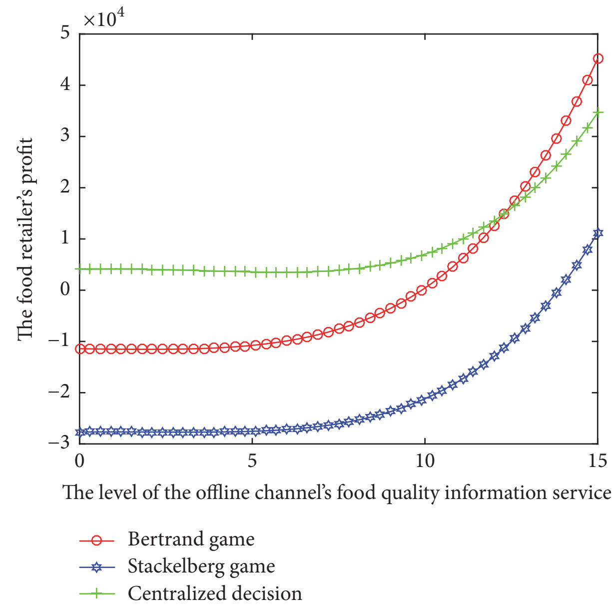

Figure 9: The relationship between the level of the offline channel's food quality information service and the food retailer's profit.

3.6. The Impact of the Level of the Offline Channel's Food Quality Information Service on the Food Processing Factory's Profit. According to (11), (25), and (35), we use $s_1 = 6$, $s_2 \in [0, 100]$, and then we use Matlab software to graph the results (see Figure 8). We analyze the impact of the level of the offline channel's food quality information service on the food processing factory's profit as follows.

In Figure 8, we see that when the food quality information service level provided by the online channel is certain, the food processing factory's profit gradually increases under decentralized decision making when the food quality information service is provided by the offline channel. In contrast, the food processing factory's profit gradually decreases under centralized decision making. Therefore, in crafting pricing strategies, the food processing factory should consider developmental changes in the level of the offline channel's food quality information service.

3.7. The Impact of the Level of the Offline Channel's Food Quality Information Service on the Food Retailer's Profit. According to (12), (26), and (36), we use $s_1 = 6$, $s_2 \in [0, 15]$, and then we use Matlab software to graph the results (see Figure 9). We analyze the impact of the level of the offline channel's food quality information service on the food retailer's profit as follows.

From Figure 9, we see that when the level of the online channel's food quality information service is certain, the food processing factory's profit gradually increases with the level of the offline channel's food quality information service. The food retailer should set the price under the Bertrand game when the level of the offline channel's food quality information service is greater than 12.3. The food retailer tends to set the price under centralized decision making when the level of the offline channel's food quality information service is less than 12.3.

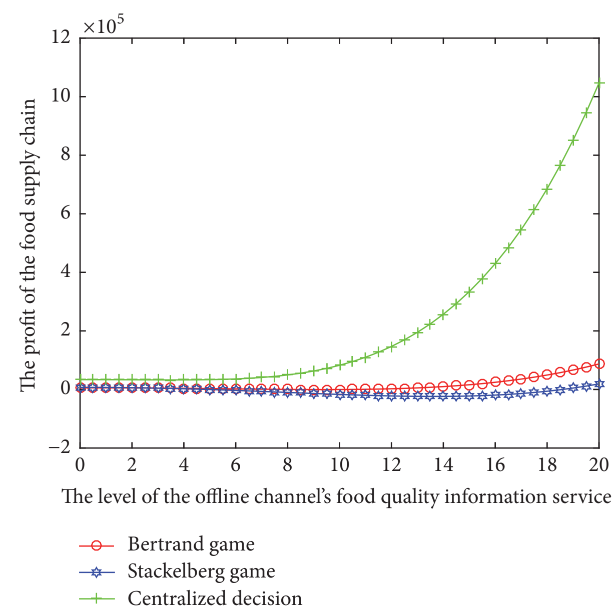

Figure 10: The relationship between the level of the offline channel's food quality information service and the total profit of the food supply chain.

3.8. The Impact of the Level of the Offline Channel's Food Quality Information Service on the Total Profit of the Food Supply Chain. Based on (13), (27), and (37), we use $s_2 = 6$, $s_1 \in [0, 10]$, and then we use Matlab software to graph the results (see Figure 10). We analyze the impact of the level of the offline channel's food quality information service on the profit of the food supply chain as follows.

As shown in Figure 10, there is an optimal profit value in the food supply chain under centralized decision making. To obtain the maximum benefit, the supply chain members should formulate their pricing strategies under centralized decision making.

Overall, when the food quality information service is provided by the offline channel, the profitability of the entire supply chain is optimal. It is optimal when the food processing factory chooses decentralized decision making and when the food retailer chooses centralized decision making. As a result, the food retailer using the offline channel to improve the food quality information services is the best decision for the entire food supply chain.

Therefore, to achieve an optimal food supply chain overall, the level of the food quality information service of the offline channel should be improved. Considering marketing strategies, the offline channel should take advantage of the nature of offline retail to meet customers' needs. For example, after the first purchase, it could improve customer experience and ensure food quality. Through the news media, it could use APP and other channels to deliver food quality information. A combination of online and offline information sources could also be used to increase the technical input and design a food quality information traceability system based on Android and QR codes to improve information sharing. At the staff level, employees should be trained in providing food quality information to enhance their understanding and to ensure accuracy and professionalism when providing such information, thus enhancing service awareness and the staff's professional ethics.

3.9. The Impact of the Quantity Discount Mechanism on the Food Retailer and the Food Processing Factory before and after Coordination. We consider the operational decisions of Nianyugou Wangu Processing Co., Ltd., which provides food retailers with a variety of discounts. The food processing factory offers returns to food retailers in the form of lower prices, which are conducive to stabilizing the partnership with downstream members of the supply chain. However, a portion of the profits of Nianyugou Wangu Processing Co., Ltd., comes from the services that it offers to retailers, which in turn enhance the profits of the food supply chain. Therefore, by examining the successful experience of Nianyugou Wangu Processing Co., Ltd., we analyze the impact of quantitative discount mechanisms on food retailers and the food processing factory using numerical examples. Then, we optimize the effective range of the quantity discount factor.

In the food supply chain under the O2O mode, the basic parameter values are as follows: $a_1 = 210$, $a_2 = 240$, $c = 100$, $\beta_1 = 2$, $\beta_2 = 1$, $\alpha_1 = 4$, $\alpha_2 = 2$, $\eta_1 = 7$, $\eta_2 = 2$.

We can compare the changes in profit for the food processing factory and food retailers before and after coordination.

Using (33), the food processing factory's profit before coordinating under the Stackelberg game is

$$\Pi_1^S = \left(p_1^S - c - \frac{\eta_1 s_1^2}{2}\right) D_1^S + \left(w_1^S - c\right) D_2^S. \tag{53}$$

The prices in the online and offline channels under the Stackelberg game are p_1^S, p_2^S, respectively; see (17) and (18), and taking p_1^S, p_2^S into (1), we can obtain the demand of the online and offline channels under the Stackelberg game, D_1^S, D_2^S, respectively. Finally, we insert the parameter values into (25) and find that the food processing factory's profit before coordination is 18354.

Using (49), the food processing factory's profit after coordination under the quantity discount mechanism is

$$\begin{aligned}\Pi_1^{QD} &= \left(p_1^{QD} - c - \frac{\eta_1 s_1^2}{2}\right) D_1^{QD} \\ &\quad + \left[\left(w_1^{QD} - kD_2^{QD}\right) - c\right] D_2^{QD}.\end{aligned} \tag{54}$$

The prices in the online and the offline channels under the quantity discount mechanism are p_1^{QD}, p_2^{QD}, respectively. Seeing (45) and (48) and inserting p_1^{QD}, p_2^{QD} into (1), we obtain the demand of the online and offline channels under the quantity discount mechanism D_1^{QD}, D_2^{QD}, respectively. Finally, we insert the parameter values into (49) and find that the food processing factory's profit before coordination is $5180k + 16303$.

Using (26), the food retailer's profit before coordination under the Stackelberg game is as follows:

$$\Pi_2^S = \left(p_2^S - w_2^S - \frac{\eta_2 s_2^2}{2}\right) D_2^S + \left(\frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2}\right) D_1^S. \tag{55}$$

The prices in the online and offline channels under the Stackelberg game are p_1^S, p_2^S, respectively; based on (17) and (18), inserting p_1^S, p_2^S into (1), we obtain the demand of the online and the offline channels under the Stackelberg game, D_1^S, D_2^S, respectively. Finally, we insert the parameter values into (33) and find that the food retailer's profit before coordination is 6688.

Using (50), the food retailer's profit after coordination under the quantity discount mechanism is

$$\begin{aligned}\Pi_2^{QD} &= \left[p_2^{QD} - \left(w_2^{QD} - kD_2^{QD}\right) - \frac{\eta_2 s_2^2}{2}\right] D_2^{QD} \\ &\quad + \left(\frac{\eta_1 s_1^2}{2} - \frac{\eta_2 s_1^2}{2}\right) D_1^{QD}.\end{aligned} \tag{56}$$

The prices in the online and offline channels under the quantity discount mechanism are p_1^{QD}, p_2^{QD}, respectively; using (45) and (48) and inserting p_1^{QD}, p_2^{QD} into (1), we obtain the demand of the online and offline channels under the quantity discount mechanism, D_1^{QD}, D_2^{QD}, respectively. Finally, inserting the parameter values into (50), we find that the profit of the food retailer before coordination is $-5180k + 7884$.

Based on the above results, the relationship between the profit and quantity discount coefficients before and after coordination between the food processing factory and the retailers under the Stackelberg game and the quantitative

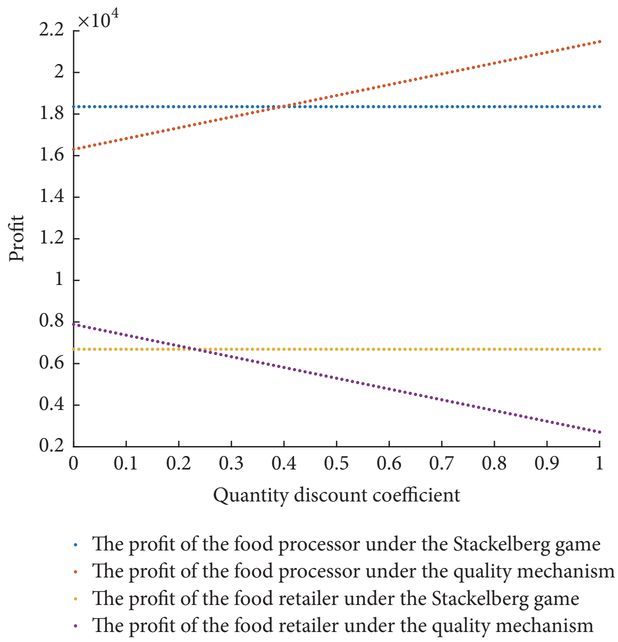

Figure 11: The relationship between profit and the quantity discount coefficients of the food retailer and the processor before and after coordination.

discount mechanism is shown in Figure 11, which is depicted graphically by Matlab software.

In Figure 11, we can observe the profit changes of the food processing factory and retailer when the quality discount coefficient has different values. The food retailer's profits decrease when the quantity of discount factors increases, and its profits are greater than the profits under the Stackelberg game. At this point in time, the profits of the food processing factory are optimized. Therefore, at this time, the coordination mechanism is effective. In fact, the food processing factory is willing to implement the volume discount mechanism as long as the profit brought by its market share resulting from the implementation of the quantity discount mechanism exceeds the price loss. The food processing factory's profits increase when the quantity of discount factors increases under the quantity discount mechanism, and when K is higher than 0.4, these profits are higher than those under the Stackelberg game. In contrast, the food retailer's profit decreases when the quantity of discount factors increases, and its profit is less than its profit under the Stackelberg game. Both 0.4 and 0.25 are critical values, and the quantity discount mechanism has advantages for both the food processing factory and the retailer. The quantity discount mechanism is effective, and the food retailer's profit is optimized. The food processing factory can share in the extra profit margins of the food retailer, which is equivalent to reducing the cost of retailers buying excess goods.

4. Conclusion

This paper analyzes the pricing coordination decisions of a food processing factory and a food retailer in a food supply chain based on the O2O mode. We also discuss the impacts of the food quality information service level on prices and profits in the food supply chain. The following conclusions are drawn based on a numerical simulation analysis.

First, we have comprehensively analyzed the impact of food quality information services on price. We observe that there is an optimal price for the food processing factory under the Stackelberg game. When the level of the offline channel's food quality information service is certain, the food quality information service level provided by the online channel is higher than the critical value. At the same time, there is an optimal price in the offline channel under the Bertrand game when the food quality information service level provided by the online channel is less than the critical value. Therefore, the food processing factory should make its price decision by adopting the Stackelberg game method, and the food retailer should make its price decision by adopting the Bertrand game method. Therefore, if the food processing factory and the retailer want to increase their profits, they should continuously improve the level of their food quality information services.

Second, we comprehensively analyze the impact of food quality information services on profits. We conclude that the food processing factory and the retailer should use centralized pricing decision making when the level of the online channel's food quality information service is certain and the level of the food quality information service provided by the offline channel is lower than the critical value. At the same time, the food processing factory and retailer should adopt the Bertrand game method and the Stackelberg game method, respectively, when the food quality information service level provided by the offline channel is higher than the critical value. Therefore, the online and the offline channels should improve the food quality information service level in terms of technology, distribution, and business strategies. Further, the reliability of information services, warehousing, and logistics is one advantage of the offline channel, but these features are often inadequate for online channels. However, efficiency, informatization, and systematization are the strengths of online channels. Hence, the two channels can strengthen their cooperation to improve the food industry.

Third, the food processing factory's profit increases when the quantity of discount factors increases under the quantity discount mechanism when K is less than 0.25, but this profit is less than that under the Stackelberg game; meanwhile, the profit of the food retailer decreases when the quantity of the discount factors increases and is higher than its profit under the Stackelberg game. The food processing factory's profit increases when the quantity of discount factors increases under the quantity discount mechanism when K is higher than 0.4, and it is higher than its profit under the Stackelberg game. In contrast, the profit of the food retailer decreases when the quantity of discount factors increases and is less than its profit under the Stackelberg game. The quantity discount coordination mechanism generally improves, and from our numerical results, we observe that a quantitative discount coordination mechanism in general can improve the profitability of the food processing factory and retailer, thereby improving the overall efficiency of the food supply chain. The value of coordinating contracts is even more pronounced when the level of the food quality information service increases. Therefore, as the main member of the food supply chain, the food processing factory should set reasonable coordination parameters for quantitative discount mechanisms to improve the efficiency of the food supply chain.

In summary, food processing factories should reduce their food quality information service costs and cooperate with food retailers with low service costs. At the same time, food processing factories should also improve the level of their food quality information services and competitiveness and thereby provide reasonable prices and food quality information services for consumers. The members of a food supply chain must consider competitors after coordinating with the other members and then make optimal competitive decisions. The competition between several food retailers and a food processing factory will be considered in future research.

Additional Points

Practical Applications. This study could be used to aid both food processing factories and food retailers in making pricing coordination decisions under the influence of a food quality information service. The study could further help food processing factories and retailers coordinate and optimize their profits. We provide recommendations based on a reasonable range of the coordination coefficient, and we recommend that food processing factories cooperate with food retailers that provide lower-cost food quality information services.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] V. A. Zeithaml, "Consumer perceptions of price, quality, and value: a means-end model and synthesis of evidence," *Journal of Marketing*, vol. 52, no. 3, pp. 2–22, 1988.

[2] A. V. Roth, A. A. Tsay, M. E. Pullman, and J. V. Gray, "Unraveling the food supply chain: Strategic insights from China and the 2007 recalls," *Journal of Supply Chain Management*, vol. 44, no. 1, pp. 22–39, 2008.

[3] G. Bosona, "Quality as an integral part of logistics management in food and agricultural supply chain," *Food Control*, vol. 33, pp. 32–48, 2013.

[4] M. M. Aung and Y. S. Chang, "Traceability in a food supply chain: safety and quality perspectives," *Food Control*, vol. 39, no. 1, pp. 172–184, 2014.

[5] K. G. Grunert, "Food quality and safety: consumer perception and demand," *European Review of Agricultural Economics*, vol. 32, no. 3, pp. 369–391, 2005.

[6] D. B. Pinto, I. Castro, and A. A. Vicente, "The use of TIC's as a managing tool for traceability in the food industry," *Food Research International*, vol. 39, no. 7, pp. 772–781, 2006.

[7] D. Folinas, I. Manikas, and B. Manos, "Traceability data management for food chains," *British Food Journal*, vol. 108, no. 8, pp. 622–633, 2006.

[8] J. C. McEntire, S. Arens, M. Bernstein et al., "Traceability (Product Tracing) in Food Systems: An IFT Report Submitted to the FDA, Volume 1: Technical Aspects and Recommendations," *Comprehensive Reviews in Food Science and Food Safety*, vol. 9, no. 1, pp. 92–158, 2010.

[9] M. M. Savino, R. Manzini, and A. Mazza, "Environmental and economic assessment of fresh fruit supply chain through value chain analysis, a case study in chestnuts industry," *Production Planning and Control: The Management of Operations*, pp. 66–78, 2013.

[10] P. Pawelzik, M. Carus, J. Hotchkiss et al., "Critical aspects in the life cycle assessment (LCA) of bio-based materials - Reviewing methodologies and deriving recommendations," *Resources, Conservation & Recycling*, vol. 73, pp. 211–228, 2013.

[11] I. Herath, S. Green, D. Horne, R. Singh, S. McLaren, and B. Clothier, "Water footprinting of agricultural products: Evaluation of different protocols using a case study of New Zealand wine," *Journal of Cleaner Production*, vol. 44, pp. 159–167, 2013.

[12] Y. Virtanen, S. Kurppa, M. Saarinen et al., "Carbon footprint of food - Approaches from national input-output statistics and a LCA of a food portion," *Journal of Cleaner Production*, vol. 19, no. 16, pp. 1849–1856, 2011.

[13] P. M. Wognum, H. Bremmers, J. H. Trienekens, J. G. A. J. Van Der Vorst, and J. M. Bloemhof, "Systems for sustainability and transparency of food supply chains - Current status and challenges," *Advanced Engineering Informatics*, vol. 25, no. 1, pp. 65–76, 2011.

[14] J. Jun, J. Kang, and S. S. Hyun, "Effects of third-party certification on patrons' service quality evaluation in the luxury-restaurant industry," *British Food Journal*, vol. 119, no. 4, pp. 771–789, 2017.

[15] C. Alasalvar, J. M. Grigor, D. Zhang, P. C. Quantick, and F. Shahidi, "Comparison of volatiles, phenolics, sugars, antioxidant vitamins, and sensory quality of different colored carrot varieties," *Journal of Agricultural and Food Chemistry*, vol. 49, no. 3, pp. 1410–1416, 2001.

[16] J. Zhang, L. Liu, W. Mu, L. M. Moga, and X. Zhang, "Development of temperature-managed traceability system for frozen and chilled food during storage and transportation," *Journal of Food, Agriculture and Environment*, vol. 7, pp. 28–31, 2009.

[17] I. Vandekinderen, J. Van Camp, F. Devlieghere et al., "Effect of decontamination on the microbial load, the sensory quality and the nutrient retention of ready-to-eat white cabbage," *European Food Research and Technology*, vol. 229, no. 3, pp. 443–455, 2009.

[18] R. Manzini and R. Accorsi, "The new conceptual framework for food supply chain assessment," *Journal of Food Engineering*, vol. 115, no. 2, pp. 251–263, 2013.

[19] S. R. Drake, J. K. Fellman, and J. W. Nelson Usda, "Agricultural Research Service Wenatchee," *Journal of Food Quality*, vol. 11, pp. 183–191, 1988.

[20] S. Seo and C. W. Shanklin, "Important food and service quality attributes of dining service in continuing care retirement Communities," *Journal of Foodservice Commerce Research*, vol. 8, pp. 41–56, 2005.

[21] A. Lianou and J. N. Sofos, "A review of the incidence and transmission of *Listeria monocytogenes* in ready-to-eat products in retail and food service environments," *Journal of Food Protection*, vol. 70, no. 9, pp. 2172–2198, 2007.

[22] R. B. Tompkin, "Control of *Listeria monocytogenes* in the food-processing environment," *Journal of Food Protection*, vol. 65, no. 4, pp. 709–725, 2002.

[23] M. D. Richard, D. S. Sundaram, and A. W. Allaway, "Service quality and choice behavior: an empirical investigation," *Journal of Restaurant and Foodservice Marketing*, pp. 93–109, 1994.

[24] M. Mattevi and J. A. Jones, "Traceability in the food supply chain: Awareness and attitudes of UK Small and Medium-sized Enterprises," *Food Control*, vol. 64, pp. 120–127, 2016.

[25] E. Lahou, L. Jacxsens, E. Verbunt, and M. Uyttendaele, "Evaluation of the food safety management system in a hospital food service operation toward Listeria monocytogenes," *Food Control*, vol. 49, pp. 75–84, 2015.

[26] P. A. Luning, L. Bango, J. Kussaga, J. Rovira, and W. J. Marcelis, "Comprehensive analysis and differentiated assessment of food safety control systems: a diagnostic instrument," *Trends in Food Science & Technology*, vol. 19, no. 10, pp. 522–534, 2008.

[27] C. Dufour, "Application of EC regulation regarding Listeria monocytogenes in ready to eat foods in retail and catering sectors in Europe," *Food Control*, vol. 22, no. 9, pp. 1491–1494, 2011.

[28] D. A. Powell, C. J. Jacob, and B. J. Chapman, "Enhancing food safety culture to reduce rates of foodborne illness," *Food Control*, vol. 22, no. 6, pp. 817–822, 2011.

[29] D. Yao, X. H. Yue, and J. Liu, "Vertical cost information sharing in a supply chain with value-adding retailers," *International Journal of Management Science*, vol. 36, pp. 838–851, 2008.

[30] D. Bin, X. Guangye, and L. Can, "Pricing policies in a dual-channel supply chain with retail service," *International Journal of Ecology and Ecosolution*, vol. 139, pp. 312–320, 2012.

[31] Y.-G. Chen, "Internet acceptance, service competition and channel profit in dual-channel supply chain," in *Proceedings of the 1st International Conference on E-Business and E-Government (ICEE '10)*, vol. 23, pp. 3235–3238, China, May 2010.

[32] F. Bernstein and A. Federgruen, "Decentralized supply chains with competing retailers under demand uncertainty," *Management Science*, vol. 51, no. 1, pp. 18–29, 2005.

[33] P. Y. Seong and T. K. Hean, "Modeling hybrid distribution channels: a game-theoretic analysis," *Journal of Retailing and Consumer Services*, vol. 3, pp. 155–167, 2003.

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Review Article

Quality and Operations Management in Food Supply Chains: A Literature Review

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We present a literature review on quality and operations management problems in food supply chains. In food industry, the quality of the food products declines over time and should be addressed in the supply chain operations management. Managing food supply chains with operations management methods not only generates economic benefit, but also contributes to environmental and social benefits. The literature on this topic has been burgeoning in the past few years. Since 2005, more than 100 articles have been published on this topic in major operations research and management science journals. In this literature review, we concentrate on the quantitative models in this research field and classify the related articles into four categories, that is, storage problems, distribution problems, marketing problems, and food traceability and safety problems. We hope that this review serves as a reference for interested researchers and a starting point for those who wish to explore it further.

1. Introduction

Food quality, including safety, has been a major concern faced by the food industry, partly due to a series of food safety crises and scandals [1]. Quality of the food products continuously changes as they move along the supply chain, which can lead to significant social, economic, and environmental consequences.

Food spoilage is one of the major issues related to food safety and quality. When food products move from farms to food processors, food retailers, and end customers, spoilage cannot be avoided. Food perishability may cause huge wastes. It is estimated by the United Nations that approximately one-third of all food produced for human consumption is wasted each year. In other reports, 40% of total production was wasted [2, 3]. The economic loss caused by food perishability and waste reached $218 billion in the US, $143 billion in Europe, and $27 billion in Canada [4–6]. In addition to the economic impacts, food perishability also caused food safety problems in many regions. According to the WHO [7], about 600 million people became ill after consuming contaminated food each year. Among them 420,000 died, including 125,000 children under the age of five years. This has raised serious concern about food safety in many countries.

The improvement of preservation technologies has provided many tools to reduce waste and improve safety in food supply chains. Many extensive literature reviews have been conducted on preservation and traceability technology adoptions in food supply chains. For example, Mercier et al. [8] provided a comprehensive literature review on time-temperature management along the food supply chain. Badia-Melis et al. [9] reviewed traceability technology adoptions in food supply chains. The adoption of various temperature control or traceability technologies allows information to be gathered to optimize inventory decisions, distribution decisions, and retail strategy even enhance safety in food supply chains.

Also, the research progress in operations management provides many opportunities for companies to reduce product waste due to decaying and to enhance food quality. Akkerman et al. [10] reviewed the quantitative operations management research on food distribution concerning food

Table 1: Searching guidelines and results.

Filter type	Descriptions and guidelines	Results
Inclusion criteria	Articles that were identified in the database search or appeared in the reference lists of one of the selected articles (i) Topic: articles that develop or apply quantitative models on food quality and operations management in food supply chain (ii) Language: limited to English (iii) Time span: 2005–2017 (iv) Paper type: academic (peer-reviewed) journal articles	
Keywords	(i) Group A keywords: "food quality", "perishable food", and "perishable products" (ii) Group B keywords: "operations management", "inventory management", "marketing", "customer behaviors", "supply chain coordination", "production planning", "quality control", and "distribution"	
Keywords search	(i) Selected online databases (e.g., Elsevier, Wiley Online, Informs, Springer, and Hindawi) (ii) All selected articles contain at least one keyword combination from Groups A and B in the title, abstract, or list of keywords	426
Exclusion criteria	(i) Not related to food quality (ii) Not related to the operations management problems (iii) Not using the quantitative methodologies	105 left

quality, food safety, and sustainability. In this article, we mainly concentrate on the quantitative operations management models related to food quality management. The goal is to present the latest research development in this field and to identify future research opportunities.

As such, we propose the following two research questions: (1) what are the state-of-the-art development and trends in quantitative operations management research regarding food quality management? (2) What gaps exist in the current research, and what are the potential future research opportunities?

This paper is organized as follows: Section 2 presents the methodology of this research along with a descriptive analysis of the existing studies. Section 3 provides details of operations management problems and related research along the food supply chain, including storage, distribution, marketing, and traceability optimization. Section 4 is about the research implications and directions for future research. Section 5 discusses the conclusions and limitations of this review.

2. Methodology

To address the research questions, the study reviews the literature of food quality management in supply chains.

2.1. Data Collection. The study aims to review published peer-reviewed articles in the targeted area from 2005 to 2017. Articles are collected from several databases, including Elsevier, Wiley Online, Informs, Springer, and Hindawi. The search was conducted based on the combination of two categories of key words; one is related to food quality and the other is related to operations management. An example of such key word combination would be "Inventory" + "food quality"; another would be "distribution" + "perishable food". Using such kind of keywords search in the databases, we found 426 articles in total.

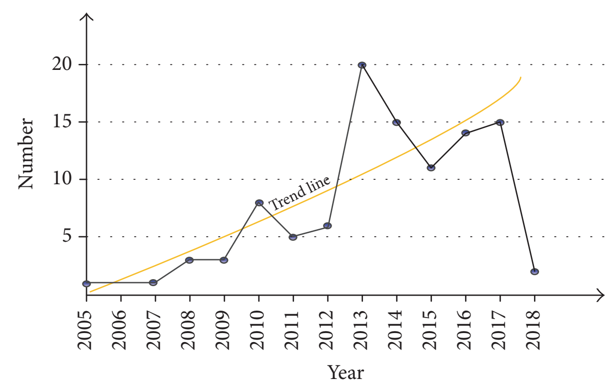

Figure 1: Distribution of articles over time.

2.2. Relevant Literature and Classification. In this stage, all articles were prudently reviewed. The searching guidelines and results are presented in Table 1. An article was removed from this study if it was not related to food quality, operations management, or not using quantitative methods. The remaining publications were then classified according to a conceptual framework proposed in Section 3.1.

2.3. Journal Statistics. The number of publications in different time periods is presented in Figure 1 to show the evolution of research interest in this topic. Between 2005 and 2017, there were a total of 105 articles on the operations management related to food quality in food supply chains. The number of the articles is rather limited before the year 2008. Then the number rises slowly from 2008 to 2012. Since 2012, scholars have become more interested in this topic. The statistics show that while the total number of research in this area is still small, interest in this field has grown rapidly in recent years.

Figure 2 presents the distribution of articles in these major publication outlets. The 105 articles included in this study were published in more than 30 journals on operations

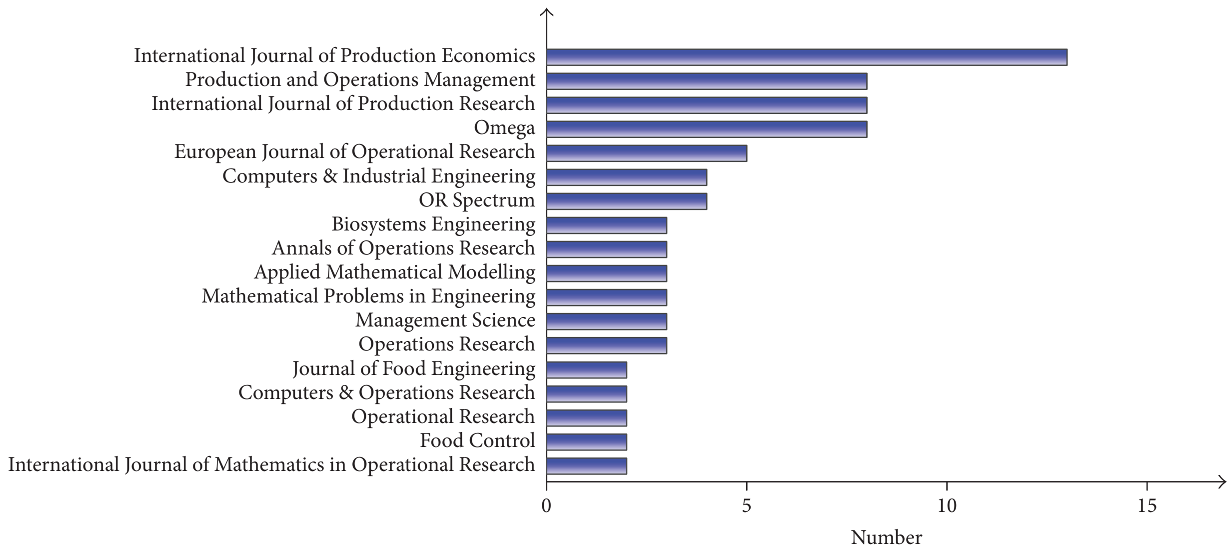

Figure 2: Distribution of journals (with number of articles ≥ 2).

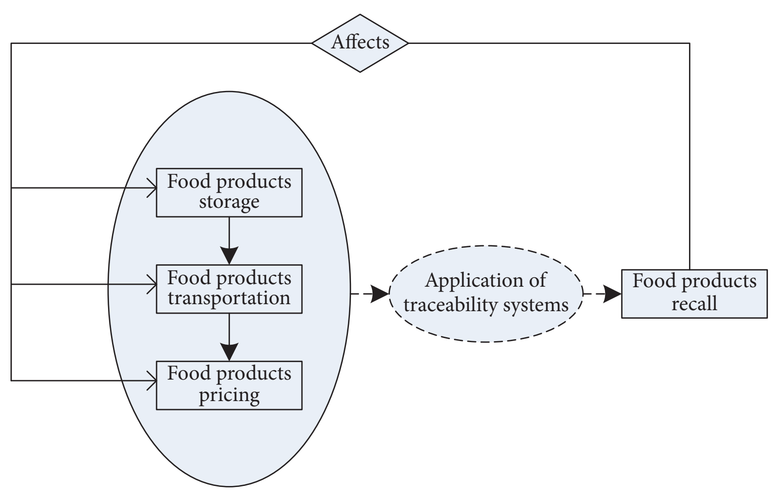

Figure 3: Conceptual framework.

management or food quality. Apparently, the top journals are International Journal of Production Economics (IJPE), Production and Operations Management (POM), International Journal of Production Research (IJPR), and Omega, which account for about one-third of the total amount. The first half of the papers contributes to about 80 percent of the total papers. After carefully reading the 105 articles, we found that these papers represent an appropriate overview of the current state-of-the-art research in the area of operations management and food quality control in food supply chains.

3. Analysis

In this section, quality and operations management problems in food supply chains are discussed in detail. More specifically, we discuss the main issues with regard to related operations management problems, followed by a discussion of research challenges.

3.1. Conceptual Framework. In order to identify the progress and gaps in the existing literature on food quality and operations management models, a conceptual framework is constructed to understand the key decisions, as shown in Figure 3. The framework helps us understand the achievements, challenges, and opportunities in the research on food quality and operations management models.

Section 3.2 summarizes the studies of inventory problems with preservation investment, followed by Section 3.3 on transportation planning problems in food supply chains. Next, Section 3.4 covers research on marketing strategies considering food quality and customers' preferences. Lastly, Section 3.5 presents the models pertaining to food traceability and food recall strategies.

3.2. Inventory Planning with Preservation Investments. A lot of researches deal with inventory management of perishable products, where their production or distribution planning is based upon an exogenous perishable rate. For example, fruits in supermarkets will perish in the selling period until they are not safe to eat. However, with the development of preservation technologies, the products' perishability can be reduced by making investment in equipment, production processes, and so on. In other words, the perishable rate highly depends on not only the natural perishable rate largely determined by environmental factors (such as temperature, humidity, light, oxygen content, and microbial content) but also the preservation technology used in the warehouse and transportation vehicles.

Although the perishing process for food products is natural and cannot be stopped, it can be slowed down by specialized equipment, such as refrigerators and humidifiers, to make temperature low and humidity suitable for certain fruits. Hence, it is practical and important to consider inventory decisions with preservation technology investment decision. Enterprises' preservation investment is often combined with other decisions, like pricing or replenishment decisions. The goal is to maximize the total profit or minimize the total cost by finding an optimal set of preservation investment level, price, or ordering quantity.

3.2.1. Single Level Supply Chain Inventory Models. Some studies focus on a single firm's preservation and inventory decisions. Hsu et al. [11] first developed an analytical Economic Ordering Quantity (EOQ) model considering both ordering policies and preservation investment for perishable products. Under the assumption that the deterioration rate is exponentially linked to the investment level, they proposed a method to determine the optimal replenishment cycle, shortage period, order quantity, and preservation technology cost so as to maximize the total profit per unit time. Numerical examples were presented to obtain further results. Lee and Dye [12] extended the model of Hsu et al. [11] by assuming that market demand is linked to inventory level and shortages are allowed and partially backlogged. An algorithm was also proposed to solve the optimization model and determine the optimal replenishment and preservation technology investment.

Dye and Hsieh [13] assumed that the deterioration cost is associated with both the preservation investment and the time instance. The objective is to find the optimal replenishment and preservation technology investment strategies while maximizing the total profit per unit time over the infinite planning horizon. Dye [14] assumed that the deterioration rate is noninstantaneous and controllable. The generalized productivity of invested capital, deterioration, and time-dependent partial backlogging rates were used to model the inventory system. The uniqueness of the global maximization was proved using fractional programming.

Chen and Dye [15] proposed a finite time horizon inventory and preservation investment model, in which the preservation investment can be different in each replenishment cycle. They utilized particle swarm optimization to solve the nonlinear programming problem. He and Huang [16] studied the optimal preservation, pricing, and ordering decisions for a kind of seasonal products. Hsieh et al. (2013) formulated an Economic Production Quantity (EPQ) model for deteriorating items with time-varying demand and controllable deterioration rate in a limited time horizon. A particle swarm optimization approach was also employed to solve the nonlinear programming problem.

Singh and Sharma [17] studied an inventory model with ramp-type demand rate, controllable deterioration rate, and two-level trade credit, in which shortages were allowed and partially backlogged. Bardhan et al. [18] also studied an inventory problem with preservation investment for noninstantaneous deteriorating products. They studied two models depending on the on-hand stock finish time: before and after the deterioration starts. Yang et al. [19] introduced the credit period theory into inventory models with preservation investment decisions. They studied a retailer selling perishable products to customers and offering a credit period to its customers to buy the products. They established a model to determine the optimal trade credit periods, preservation technology investment, and ordering strategies that maximize the total profit over a finite planning horizon.

Unlike previous studies, Dye and Yang [20] treated the selling price as a decisions variable. They considered customers' reference price behaviors and proposed a joint dynamic pricing and preservation technology investment model for a perishable inventory system with time- and price- sensitive demand. Theoretical results were obtained to demonstrate the existence of an optimal solution for the inventory problem. A simple iterative algorithm was utilized to solve the proposed model by employing the theoretical results. Features of the proposed model were illustrated with sensitivity analysis.

Kouki et al. [21] extended the known (r, Q) inventory models by assuming products are perishable. They studied the impacts of the application of Time Temperature Integrator (TTI) technology on the inventory management decisions. The TTI technology enables firms to accurately monitor products' freshness and gives information on products' remaining shelf lives. Zhang et al. [22] studied dynamic service investment problem simultaneously with preservation investment for perishable products. The analytical solution for dynamic service investment was obtained under the given sales price, preservation technology, and replenishment cycle by solving an optimal control problem. The impact of common resource constraint on the optimal investment policy was investigated. They found that for a relatively low common resource capacity, the firm prefers to invest in service improvement rather than preservation technology. Mishra [23] studied an EPQ problem considering uncertain and controllable deterioration rate. Following Day and Yang (2016), Mishra et al. [24] studied an inventory model that considers demand rate as a function of stock and selling price. They established an EOQ model considering preservation investment, product deterioration, and two types of backordering scenarios. Li et al. [25] studied an inventory control problem considering the optimal packaging decisions to extend the product shelf life. High quality packaging helps to better preserve the products but leads to higher costs for sellers. The goal is to minimize the total costs by choosing an appropriate packaging strategy.

3.2.2. Two Level Supply Chain Inventory Models. The preservation investment problem has also been studied in two-level supply chains. Tayal et al. [26] developed a two-level supply chain model, in which the products are perishable and the deterioration rate is controllable. Also, customers' demand is sensitive to the products' expiration rate. Zhang et al. [27] studied a two-level inventory model for deteriorating items with controllable deterioration rate and price-dependent demand. They derived the optimal decisions for both the decentralized and the centralized models. They found that the two-level supply chain can be coordinated with a revenue sharing and cooperative investment contract. The results show that only when the revenue sharing rate lies roughly between 1/2 and 3/4 can the contract perfectly coordinate supply chains in most cases, which has an important implication in supplying chain coordination of deteriorating items with preservation investment. Shah et al. [28] studied an inventory model in a two-level supply chain consisting of a manufacturer and a retailer. The manufacturer offers a trade credit to the retailer and the retailer's deterioration rate is time dependent and linked with preservation investment. The retailer also offers partial trade credit to the buyers. Giri et al. [29] studied a two-level supply chain model with product deterioration, controllable deterioration rate, and unreliable production.

3.2.3. Multiple Facility Inventory Models. Researchers also considered the preservation investments for a multifacility supply chain. Cai et al. [30] studied the optimal ordering policy and fresh product keeping efforts in a multilevel supply chain with long transportation distance and high deterioration rate for intransit products. Yu and Nagurney [31] developed a network-based food supply chain production model under oligopolistic competition and perishability, with a focus on fresh produce. The product differentiation is characterized by the different product freshness and food safety concerns, as well as the evaluation of alternative technologies associated with various supply chain activities.

Tsao [32] studied a joint model considering location, inventory, and preservation decision-making problem for noninstantaneous deteriorating items under delay in payments. In the author's model, an outside supplier provides a credit period to the wholesaler that has a distribution system with distribution centers. The goal is to determine the locations, the number, the replenishment time of the distribution centers, and the preservation investments. Tsao [33] studied the network design problems in a supply chain including distribution centers and retailers considering trade credit arrangements, preservation investment, and product deterioration. The goal is to determine the optimal locations of distribution centers, assignment of retailers to distribution centers, replenishment time, and preservation investment to maximize the total profit.

3.2.4. Summary. In this subsection, the inventory problems combined with food preservation investment is presented. We classify the existing papers into three categories for different supply chain structures, that is, single level supply chain, two-level supply chain, and multilevel supply chain. The research contributions are presented in each part.

3.3. Transportation Planning for Perishable Products. In this subsection, we discuss the transportation planning in food supply chains considering food quality degradation. In economy, transportation plays an important role, which accounts for two-thirds of the total logistics cost and affects the level of customer service. In reality, food supply chains stretch from upstream agricultural farms to downstream consumers, with intermediate manufacturers, foodservice providers, and sellers in the middle. Along the distribution process, food products may perish and temperature control becomes crucial for supply chain partners to reduce wastes and enhance food quality and food safety. To enhance the profitability and competitiveness, many enterprises strive to handle the issue of product perishability so as to maintain the value of their products.

The transportation planning problems are mainly concerned with the optimization of delivery routes, delivery quantities, and delivery time. Transportation modes, such as flights, cargo vessels, or trains, should also be considered. Although great progress has been made in this direction in terms of considering product perishability properties, challenges still exist.

Transportation planning mainly deals with vehicle routing problems (VRP). When considering product perishability, more factors should be reconsidered in this research area. First, food safety is a main concern when enterprises distribute the food products from manufacturer to retailers and customers. For example, Rijgersberg et al. [34] developed a simulation model of the distribution chain of fresh-cut iceberg lettuce under the consideration of quality and safety during distribution stage. Second, different types of perishable products should be stored in different conditions during transportation. Because the storage temperatures for chilled meat and fresh vegetable are different, a vehicle may be divided up into multiple compartments with different temperature controls [35]. This makes the transportation planning more complex and more challenging. Third, distribution planning of the food products is often linked to customers' preferences and satisfactions [36]. In real life, the fresher the products, the higher the price. Shorter delivery time helps to maintain the freshness, yet it increases the total transportation cost.

3.3.1. Transportation Planning Considering Various Factors. During the transportation of perishable products, factors like the product quality, the product safety, the transportation mode, the preservation conditions, or multifirms' coordination all have significant impacts on optimal decisions.

Dabbene et al. [37] assumed that quality of the perishable products during transportation is directly linked to time and solved a distribution planning model by a heuristic approach. Quality change may lead to food safety problems. Rijgersberg et al. [34] also developed a simulation model of the distribution chain of fresh-cut iceberg lettuce under the consideration of quality and safety during distribution stage. The main purpose was to study the impacts of product life cycle, customer purchasing behaviors, and distribution lead time reduction on distribution strategies.

Some researchers demonstrate that transportation modes affect the optimal decisions significantly. Ahumada and Villalobos [38] considered transportation modes in their integrated production and distribution optimization models. They proposed that supply chain partners need to choose from the transportation modes of truck, rail, or air to distribute their packaged perishable products under different conditions. The impacts of refrigeration cost were discussed in Dabbene et al. [39]. Rong and Grunow [40] studied the impacts of product dispersion during distribution on optimal distribution planning strategies. Although dispersion enhances supply chain efficiency, it also causes food safety problems. Their approach allowed decision-makers to deal with the tradeoff under different risk attitudes. Cai and Zhou [41] studied the optimal production and delivery policies when facing two markets (i.e., local market and foreign market) and the transportation to foreign market may be disrupted. An optimal policy was proposed to minimize the total cost. Eleonora and Jesus (2015) analyzed the schemes for food delivery to urban food sellers. They studied the impacts of traffic regulations, delivery services, and an urban distribution center on the distribution efficiency in a case study of Parma, Italy. Ketzenberg and Ferguson [42] studied the value of information sharing between the seller and the supplier in a two-level supply chain. They showed in the numerical tests that information sharing not only improves profits of the two parties, but also benefits customers by enhancing product freshness.

In addition to the impacts of quality, safety, and transportation modes, Grillo et al. [36] proposed a mixed integer mathematical programming model to study an order promising process in fruit supply chains with subtypes of products considering various natural factors, such as land, weather, or harvesting time. Bilgen and Günther [43] studied an integrated problem for production and distribution planning. They considered two different transportation modes in the distribution stage between plants and distribution centers: the full truck load and less than truck load.

Soysal et al. [44] studied a routing problem with multiple suppliers and customers considering food perishability and horizontal collaboration between supply chain partners. They found that horizontal collaboration may reduce wastes and carbon emission and increase distribution efficiency of the whole supply chain. They used an experiment to study the impacts of related factors and found that the gains are highly sensitive to the supplier size or the maximum shelf life of the products.

3.3.2. Transportation Combined with Inventory Problems. It is common that transportation planning is often related to inventory planning problems. The combined inventory-routing approaches not only solve the short term VRP problems, but also help to overcome the long term production planning problems.

Rong et al. [45] studied a joint production and distribution planning model under the consideration of food quality degradation. In addition to routing and storage planning decisions, the firm also makes decisions on the temperature during storage and distribution. The problem was solved with a generic approach. Farahani et al. [46] studied an integrated production and distribution planning model for a kind of fast perishable food product. To deal with the fast perishability, they proposed a policy to shorten the time interval between production and distribution. Adelman and Mersereau [47] studied a dynamic capacity allocation problem when customers' ordering quantity is correlated to fill rates in the past. In their model, customers risk attitudes to the fill rates were different. Given customers' differentiated behaviors, a dynamic rationing policy of the fill rates was proposed to achieve higher profit and higher customer satisfaction.

Coelho and Laporte [48] studied an integrated replenishment, distribution, and inventory management problem when products have various lifetimes. They showed in the numerical experiments that the optimal policy is either to sell the oldest available items first to avoid spoilage, or to sell the fresher items first to increase revenue. Devapriya et al. [49] studied an integrated production and distribution scheduling problem for perishable products in a multiechelon chain. Their objective was to determine the optimal fleet size and trucks' routes in order to minimize the aggregated cost. Unlike the previous research, their study captured both production and distribution planning under the consideration of limited lifetime of the products. A mixed integer programming model was formulated to solve the problem and heuristics based on evolutionary algorithms were provided to resolve the models. Liu et al. [50] studied the dynamic inventory rationing problem for perishable products over multiple periods for a wholesaler. The rationing strategy was not only determined by the perishable properties of the products but also affected by the uncertain selling price in the future periods. Qiu et al. [51] studied a generalized production-inventory-routing problem for perishable products. They have discussed several inventory management policies to illustrate the real-world applications of the proposed models.

More works can be seen in Bilgen and Günther [43], Makkar et al. [52], Cai et al. [53], Rahdar and Nookabadi [54], Uthayakumar and Priyan [55], Jia et al. [56] Diabat et al. [57], Lee and Kim [58], Gaggero and Tonelli [59], Belo-Filho et al. [60], Priyan and Uthayakumar [61], Seyedhosseini and Ghoreyshi [62–64], Sel et al. [65], Mirzaei and Seifi [66], Drezner and Scott [67], and Dobhan and Oberlaender [68].

3.3.3. Transportation Combined with Network Design Problems. In food industry, there exist many kinds of distribution networks. In practice, the network design problem is to jointly optimize the location of hubs and the flows from upstream manufacturers to downstream retailers and customers. Distribution network design plays a key role in reducing transportation costs and maintaining quality of perishable products in food supply chains. However, many of the existing models on distribution network design only consider single period problems, which cannot be used to solve the problems for perishable products with time limitations within the networks. To solve the network design problems, many new types of mathematical models and innovative algorithms were developed in the last decade.

Firoozi et al. [69] studied a network design problem for perishable products which have limited storage time during transportation. Their model attempted to balance the benefit from enhancing storage conditions to maintain products quality and the associated costs to improve storage conditions. An efficient Lagrangian relaxation heuristic algorithm was developed to solve the proposed model. Firoozi et al. [70] studied a similar network design problem considering product perishability. They proposed a memetic algorithm (MA) and proved that it works more efficiently than the Lagrangian relaxation heuristic algorithm. Unlike Firoozi et al. [69] and Firoozi et al. [70], Firoozi and Ariafar [71] considered a fluctuated expected lifetime of perishable products during transportation due to unusual weather condition or malfunction of transportation and storage facilities.

Drezner and Scott [67] studied an inventory and location decisions in a network with a single distributor and multiple sales outlets for perishable products. Computational experiments showed that the location of the distribution center affects the inventory decisions significantly. Tsao [32] considered the joint location, inventory, and preservation decisions for a two-level supply chain with a supplier, a wholesaler, and multiple distribution centres. Algorithms were proposed to solve the nonlinear optimization models. Dulebenets et al. [72] studied an intermodal freight network design problem which deals with the decisions of production, inventory, and transportation. The numerical cases show that decaying cost significantly affects the transportation modes and the associated distribution routing. Rashidi et al. [73] formulated a biobjective mathematical model to optimize the joint location-inventory decisions in a network for perishable products. A Pareto-based metaheuristic approach was proposed to solve the models. de Keizer et al. [74] studied the network design problems for perishable products under different product quality and delivery lead time. The objective was to study the impacts of quality decay and its heterogeneity on optimal network design strategies. They used a mixed integer programming approach to formulate the model, which is to maximize the total profit under quality constraints. The results showed that heterogeneous product quality decay has significant impacts on network design and profitability.

3.3.4. Summary. In this subsection, the papers on food products transportation problems are reviewed. In this area, people often study the transportation problems with various factors including product quality, product safety, transportation mode, preservation conditions, and multifirms' coordination. In addition, in real practice, transportation planning is often combined with inventory planning or network design or both. As such, we presented a comprehensive review of papers studying joint decisions of inventory-transportation problems and network design-transportation problems.

3.4. Quality Based Pricing for Perishable Products. In this subsection, we summarize the up-to-date research on pricing problems related to time-linked quality for perishable products. Recently, customers are more concerned about food safety and become more sensitive to food quality when purchasing food products. The demand for food products is highly linked to food quality. Due to the nature of food products, quality drops with time following a dynamic state. Therefore, static pricing strategies may result in inappropriate quality control and excessive inventories in food supply chains. Many scholars did research on the dynamic pricing strategies to help firms reduce waste and enhance profit and food safety.

3.4.1. Models with Single Products and Homogenous Customer Preferences. In today's food supply chains, various technologies (e.g., ratio frequency identification technology (RFID) and time temperature indicator (TTI)) can be adopted to capture product information (e.g., temperature, humidity, and the time period) automatically. Thus, this kind of information can be used to predict food quality and remaining shelf life, which supports the decisions on inventory control and pricing decisions. Besides, customers are often sensitive to the product quality and they alter their purchasing decisions toward products with different qualities.

Ferguson and Koenigsberg [75] established a two-period model, considering product quality decline, quality dependent demand, and competition. The research aims to optimally determine the prices and inventory to maximize the total profit. Blackburn and Scudder [76] studied supply chain strategies together with pricing decisions based on perishable products' marginal-value-of-time (MVT). Sainathan [77] studied the pricing and replenishment strategies for a perishable product with two-period lifetime when customers' utility is quality sensitive. In each period, new products and old products were differently priced to maximize the total profit. Wang and Li [78] proposed a real time quality based dynamic pricing model for perishable foods in a supply chain with quality sensitive customers. Compared to the static pricing strategy, this quality-based pricing strategy helps reduce food spoilage waste and bring more profit to the retailers. A real case was also used to illustrate the results in the analytical models.

Adenso-Díaz et al. [79] proved that dynamic pricing can significantly reduce the total waste of the perishable products, as Wang and Li [78] demonstrated. However, the spoilage reduction may come as a loss in total revenue that can vary dramatically, depending on the scenario and the speed of the price discount strategy. Also, based on the assumption that retailers can utilize time-temperature-indicator-based automatic devices, Herbon et al. [80] studied an optimal dynamic pricing model considering product perishability and customers' satisfactions. Herbon and Khmelnitsky [81] studied an integrated ordering and dynamic pricing model for perishable products when customers are highly sensitive to food quality. Unlike Wang and Li [78], they studied a continuous dynamic problem rather than a discrete one. They also showed that the efficiency of the dynamic approach depends on the form of demand incorporated into the model.

3.4.2. Models Considering Product Differentiation. Product differentiation is a factor that the retailers should consider when they make ordering or pricing decisions. When product lifetime is considered, products at different ages are different but still substitutable, which may affect customer purchasing behaviors. Chew et al. [82] studied an integrated ordering and dynamic pricing problem for a kind of perishable product with multiperiod lifetime. The products at different ages, mutually substitutable, are all available in the market. The results showed that, under the assumption of product substitutions, the retailer's total profit increases significantly. Chen et al. [83] studied a combined pricing and inventory control problem considering product perishability with a fixed shelf life over a finite horizon. Heuristic policies were proposed to solve the models. In addition, they also proved that their model is applicable when the product's lifetime is stochastic.

Herbon [84] also studied the pricing policies for a kind of perishable product with different ages. The author compared two strategies: fixed pricing and differentiated pricing. The author found that an optimal pricing policy is to implement price discrimination with respect to consumers' sensitivity to freshness, while dynamically changing the price over time, starting with a lower price at the early stages of the product's shelf life and increasing it at a later stage. Hu et al. [85] established a joint inventory and price markdown model considering customers' strategic behaviors. To reduce costs, the firm can either choose to discard the leftover inventory or set a clearance price. Li et al. [86] studied an inventory control problem with clearance sales strategies and product perishability. They proposed two myopic heuristics to solve the problems with partial information.

3.4.3. Models Considering Heterogeneous Customer Preferences. Customers often have different valuations towards the same kind of products with same quality. Such customer heterogeneity on product quality for perishable products has also been considered. Akçay et al. [87] studied a dynamic pricing problem of a firm which sells multiple differentiated products with linear random consumer utilities. Gallego and Hu [88] studied a dynamic price competition problem in an oligopolistic market when products perish over time. Herbon [89] proposed a pricing model under consumer heterogeneity in consumers' sensitivity to freshness of a perishable product. He compared the model with and without the consideration of such heterogeneity. Also evaluated are the conditions in which a dynamic pricing policy is beneficial either to the retailer or to the consumer, as compared with a static pricing policy.

In Herbon [90], customers were also assumed to be heterogeneous in their sensitivity to freshness, that is, their willingness to pay more for fresher products. A dynamic pricing model was developed to evaluate the extent to which both the retailer and the customers benefit from the dynamic pricing policy as opposed to the static pricing policy. Herbon [91] also studied a model with multiple competing perishables with different remaining lifetimes and selling prices. It is found that when customers are homogeneous in their preferences, single-product-age operational mode outperforms the multiple-product-age operational mode. Herbon [92] studied an inventory and pricing model considering customers' heterogeneity towards the real time quality of the perishable products. The effects of remaining shelf-life, price, and perceived quality on demand were investigated in their models. Also, it is shown that highly heterogeneity can benefit the sellers because more products will be sold. In addition, Herbon [93] demonstrated that customer information is crucial to determine firms' pricing decisions for perishable products and customers' heterogeneous preference for product freshness.

3.4.4. Models Combined with Inventory Decisions. In many situations, inventory policies and pricing policies are mutually affected in perishable food supply chains. Pasternack [94] studied a pricing problem for a kind of perishable product combined with customer returns. The author showed that full credit provided by the manufacturer is effective in coordinating the supply chain when there is a single retailer. However it is not effective when facing multiple retailers. Li et al. [95] studied the pricing problem together with the inventory decisions in which price is linked to demand and products have two-period lifetime. Li et al. [96] assume that product perishability affects demand. Based on this assumption, they studied the joint dynamic pricing and inventory control problems for perishable products when the seller cannot sell new and old products at the same time. In each period, the seller determines to sell new products and makes replenishment policies or to sell old products and dispose of the inventory at the end of the period. The study shows counterintuitive result that profit maximization does not guarantee lower expirations.

Chen and Sapra [97] studied a joint pricing and inventory decisions for a perishable product with two-period lifetimes. They compared the first-in-first-out with first-in-last-out strategies and found that bigger orders should be placed in the FIFO system. Chung and Erhun [98] studied a two-level supply chain coordination problem considering perishable products with two periods of shelf life. Kaya and Polat [99] studied a problem of jointly determining the optimal pricing and inventory replenishment strategy for a deterministic perishable inventory system in which demand is time and price dependent. The price adjustment cost (also called Menu cost) is considered when the seller changes its selling price during the lifetime of the products. Chen et al. [100] also considered Menu cost in their integrated dynamic inventory and pricing decisions models. They found that when Menu cost is moderate, a one-time price adjustment price policy outperforms the multitime price adjustment policy. Chua et al. [101] studied the optimal price discount and replenishment policies for a perishable product with short lifetime and uncertain demand.

3.4.5. Summary. In reality, customers are sensitive to the food qualities. Thus, to ensure the profit gains, firms need to provide more fresh products to customers. In the presented models, customers' preference is directly linked to the product quality in each instance. In the first part, researchers studied the single product pricing problems with homogenous customers' preference. Then models with multiple products or multiple types of customers are presented. Lastly, ordering decisions combined with pricing decisions are reviewed.

3.5. Quantitative Models of Food Traceability and Food Recall. In this subsection, we discuss the quantitative models using the information of traceability, which aims to improve product safety and helps firms reach financial targets. Food safety crisis can happen at any stage of food supply chains. Food traceability systems can record product attributes, such as quality and safety parameters, which can be used to capture information about ingredients, processing, storage, dates (sell-by, use-by), and so on. When a food safety crisis occurs, the sold products should be recalled from the customer to mitigate the negative effects. Governments have realized the importance of food traceability and built food traceability system in many countries. For example, Hong et al. [102] discussed the financial model for applying Radio Frequency Identification (RFID) technology to a food traceability system in Taiwan. In addition, food crisis can bring great loss to enterprises. The application of traceability systems helps avoid such loss by reducing the impacts of food crisis. Required for regulatory and/or commercial purposes, they have been widely used to resolve the issues of product recall and food safety [103, 104].

The traceability systems not only improve social welfares, but also contribute to firms' financial benefits. Dupuy et al. [105] studied an optimization problem for food products under food quality risks and traceability systems. Under the given information, using a dispersion strategy, the firms can reduce the quantity of the recalled products, thus minimizing their costs. Their research showed that the traceability systems help mitigate food risks to customers. Wang et al. [106] studied an optimization problem considering food traceability in a multilevel supply chain to achieve desired product quality and minimizing the impact of product recall in an economic manner. They showed that utilizing traceability systems and traceability information contributes to the reduction of food quality risks. Wang et al. [107] also developed an integrated optimization model in which the traceability factors are incorporated with operations factors to determine the production batch size and batch dispersion. Resende-Filho and Hurley [108] studied the impacts of information asymmetry in a two-level supply chain with a supplier and a retailer implementing a traceability system. The retailer can offer payment to the supplier to induce its food safety effort. They found that traceability based batch dispersion can substitute for the retailer's payments. They also showed that mandatory implementation of the traceability system may not lead to higher food safety, because it increases the firms' costs.

Piramuthu et al. [109] studied the recall problem in a three-level food network in which the products have contamination risks. They incorporated the long delay and the inaccuracy properties of the contamination source identification in the optimization models. Comba et al. [110] proposed an optimization model to manage perishable bulk products under the use of traceability system. Although the implementation of food traceability systems helps reduce food safety risks in society, companies may hesitate to do so if the recall cost or the traceability system implementation cost is too high. For most companies, their first goal is to gain financial benefits. As such, managers have to balance the cost incurred by food quality risks and that of recall of products or the implementation of the traceability systems. Memon et al. [111] proposed an integrated optimization model to minimize the expected loss to shareholders in recall crisis using batch dispersion methodology and taking into consideration recall costs. It is shown that higher traceability level decreases the stakeholders' losses due to recall but increases operational cost. Zhu [112] demonstrated that significant investment cost acts as a major obstacle for the diffusion of traceability systems in the food industry. They studied the economic outcomes for the implementation of a RFID-enabled traceability system in a two-level perishable food supply chain. Considering customers' perceptions of food quality and safety when using the traceability system, they proposed a dynamic pricing scheme, which helps reduce waste and improve the seller's performance. Dai et al. [113] also studied the pricing and tracking capacity decisions considering different levels of food tracking cost and recall cost. Results show that there always exists a unique tracking capability and retailing/wholesale price with closed-form solutions to optimize the overall supply chain profit.

In summary, the application of traceability system can help to optimize the recall strategies when food crisis happens, therefore enhancing food safety. In the quantitative operations management models, when considering food traceability and food recall, inventory planning strategies [106, 107], transportation planning strategies [109], and marketing strategies [112, 113] will be changed. However, there is limited research on this area and more works can be done.

4. Directions for Future Research

In this section we give our suggestions for some future research topics. Although progress has been made in operations management that accounts for food quality in recent years, there are still some challenges, which ought to be overcome in future research.

First of all, in the research area of inventory planning and transportation planning, more works should be done to formulate and solve stochastic optimization problems. It is widely agreed that demand can never be a deterministic parameter in this fast changing world. However, among the papers we reviewed, lots of them assume that demand is a constant parameter, or a price/quality dependent parameter. This assumption is quite unrealistic, which restricts the practicability of the proposed models. Although some papers have studied stochastic problems, no breakthrough occurs during the recent years. In this area, there are two directions for the researchers. One direction is to formulate new mathematical models to solve more realistic problems and solve them with existing methods. Another way is to find new methods to solve the stochastic models, which is more challenging and more important for the improvement of this research area.

Next, supply chain disruption should be considered in the existing models. Disruption can happen at any stage of the food supply chain. It can happen either at the production stage, or at the transportation stage due to various reasons including weather changing, vehicle damaging, and machine breakdown. Compared to normal products, disruption can even cause more severe damage in the food industry due to the short lifetime of the food products. Because, when the distribution is delayed, quality of the products will deteriorate in a short time. The prevalence of supply chain disruption in food supply chains makes it crucial to enterprises in the decision-making process. However, supply chain disruption is seldom incorporated in the reviewed studies. In the future, one can reformulate the existing models by introducing supply chain disruptions into one of the distribution phases (inventory, transportation, and retailing) or into multiple phases.

In addition, food quality should be modeled in more practical ways. In the existing body of literature, food quality decaying is roughly modeled and approximated with inaccurate parameters. The approximation does not guarantee the applicability of the models to all products. In future research, more realistic factors need to be considered in modeling food quality in OM models, such as fast changing quality status, chemical and microbial properties of the food, and environmental conditions.

Furthermore, the forward distribution and backward recall problems should be integrated. In the papers on distribution problems, some people studied the location problem. Also, in the recall problems, the location of the recall point also serves as a very important parameter. Therefore, when designing a network, enterprises should consider the forward and backward flows simultaneously. In the future, one can formulate the models with both the distribution problems and the recall problems jointly, with a goal to enhance the firms' benefit and the food safety.

Last, it is also a future research direction to incorporate new product tracking or temperature control technologies. With these new technologies, additional information will be obtained and stored. This will lead to more advanced decision-making on food quality, more precise inventory control, and more efficient distribution systems.

5. Conclusions

In this paper, we have reviewed the operations management research on food quality and safety. Unlike other disciplines that study food quality, the Operations Management (OM) field has focused on using optimization models to capture the effects of important operational variables (e.g., inventory, routing, and pricing) on both economic and social benefits. In some studies, food quality is modeled as a constraint to the storage or distribution time, while in others, it is modeled as a decreasing parameter which depends on the required preservation conditions or time. We classify the literature into four categories, ranging from inventory decision for perishable food products, distribution problems for perishable food products, and dynamic pricing decisions for perishable food products to operations management for food traceability and safety. Furthermore, we survey the research contributions of the literature, discuss the up-to-date research development, and identify challenges for further research within each category. The importance of product quality is reflected in the current research, in terms of both research contributions and the variety of the methodologies used. The future research agenda is also proposed to enrich the understanding of various kinds of operations management decisions and food quality.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] M. M. Aung and Y. S. Chang, "Traceability in a food supply chain: safety and quality perspectives," *Food Control*, vol. 39, no. 1, pp. 172–184, 2014.

[2] FAO, *Global food losses and food waste – extent, causes and prevention*, 2011, http://www.fao.org/docrep/014/mb060e/mb060e.pdf.

[3] NRDC, *Wasted: how America is losing up to 40 percent of its food from farm to fork to landfill*, 2012, https://www.nrdc.org/sites/default/files/wasted-food-IP.pdf.

[4] L. Young, "Our biggest problem? Were wasting food. Available from," *Accessed on*, 2012, http://www.canadiangrocer.com/top-stories/what-a-waste-19736.

[5] ReFED, *The multi-billion dollar food waste problem*, 2015, http://www.refed.com/?sort=economic-value-per-ton.

[6] FUSIONS, *Estimates of European food waste levels*, 2016, http://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf.

[7] *WHO's first ever global estimates of foodborne diseases find children under 5 account for almost one third of deaths*, WHO World Health Organization, 2015, http://www.who.int/mediacentre/news/releases/2015/foodborne-diseaseestimates/en/.

[8] S. Mercier, S. Villeneuve, M. Mondor, and I. Uysal, "Time–Temperature Management Along the Food Cold Chain: A Review of Recent Developments," *Comprehensive Reviews in Food Science and Food Safety*, vol. 16, no. 4, pp. 647–667, 2017.

[9] R. Badia-Melis, P. Mishra, and L. Ruiz-García, "Food traceability: New trends and recent advances. A review," *Food Control*, vol. 57, pp. 393–401, 2015.

[10] R. Akkerman, P. Farahani, and M. Grunow, "Quality, safety and sustainability in food distribution: A review of quantitative operations management approaches and challenges," *OR Spectrum*, vol. 32, no. 4, pp. 863–904, 2010.

[11] P. H. Hsu, H. M. Wee, and H. M. Teng, "Preservation technology investment for deteriorating inventory," *International Journal of Production Economics*, vol. 124, no. 2, pp. 388–394, 2010.

[12] Y.-P. Lee and C.-Y. Dye, "An inventory model for deteriorating items under stock-dependent demand and controllable deterioration rate," *Computers & Industrial Engineering*, vol. 63, no. 2, pp. 474–482, 2012.

[13] C.-Y. Dye and T.-P. Hsieh, "An optimal replenishment policy for deteriorating items with effective investment in preservation technology," *European Journal of Operational Research*, vol. 218, no. 1, pp. 106–112, 2012.

[14] C.-Y. Dye, "The effect of preservation technology investment on a non-instantaneous deteriorating inventory model," *OMEGA - The International Journal of Management Science*, vol. 41, no. 5, pp. 872–880, 2013.

[15] Y.-R. Chen and C.-Y. Dye, "Application of particle swarm optimisation for solving deteriorating inventory model with fluctuating demand and controllable deterioration rate," *International Journal of Systems Science*, vol. 44, no. 6, pp. 1026–1039, 2013.

[16] Y. He and H. Huang, "Optimizing Inventory and Pricing Policy for Seasonal Deteriorating Products with Preservation Technology Investment," *Journal of Industrial Engineering*, vol. 2013, pp. 1–7, 2013.

[17] S. R. Singh and S. Sharma, "A global optimizing policy for decaying items with ramp-type demand rate under two-level trade credit financing taking account of preservation technology," *Advances in Decision Sciences*, vol. 2013, Article ID 126385, 2013.

[18] S. Bardhan, H. Pal, and B. C. Giri, "Optimal replenishment policy and preservation technology investment for a non-instantaneous deteriorating item with stock-dependent demand," *Operational Research*, pp. 1–22, 2017.

[19] C.-T. Yang, C.-Y. Dye, and J.-F. Ding, "Optimal dynamic trade credit and preservation technology allocation for a deteriorating inventory model," *Computers & Industrial Engineering*, vol. 87, article no. 4061, pp. 356–369, 2015.

[20] C.-Y. Dye and C.-T. Yang, "Optimal dynamic pricing and preservation technology investment for deteriorating products with reference price effects," *Omega* , vol. 62, pp. 52–67, 2016.

[21] C. Kouki, E. Sahin, Z. Jemaï, and Y. Dallery, "Assessing the impact of perishability and the use of time temperature technologies on inventory management," *International Journal of Production Economics*, vol. 143, no. 1, pp. 72–85, 2013.

[22] J. Zhang, Q. Wei, Q. Zhang, and W. Tang, "Pricing, service and preservation technology investments policy for deteriorating items under common resource constraints," *Computers & Industrial Engineering*, vol. 95, pp. 1–9, 2016.

[23] U. Mishra, "An inventory model for controllable probabilistic deterioration rate under shortages," *Evolving Systems*, vol. 7, no. 4, pp. 287–307, 2016.

[24] U. Mishra, S. Tiwari, A. A. Shaikh, and G. Treviño-Garza, "An inventory model under price and stock dependent demand for controllable deterioration rate with shortages and preservation technology investment," *Annals of Operations Research*, vol. 254, no. 1-2, pp. 165–190, 2017.

[25] Q. Li, P. Yu, and X. Wu, "Shelf Life Extending Packaging, Inventory Control and Grocery Retailing," *Production Engineering Research and Development*, vol. 26, no. 7, pp. 1369–1382, 2017.

[26] S. Tayal, S. R. Singh, R. Sharma, and A. Chauhan, "Two echelon supply chain model for deteriorating items with effective investment in preservation technology," *International Journal of Mathematics in Operational Research*, vol. 6, no. 1, pp. 84–105, 2014.

[27] J. Zhang, G. Liu, Q. Zhang, and Z. Bai, "Coordinating a supply chain for deteriorating items with a revenue sharing and cooperative investment contract," *OMEGA - The International Journal of Management Science*, vol. 56, pp. 37–49, 2015.

[28] N. H. Shah, U. Chaudhari, and M. Y. Jani, "Optimal policies for time-varying deteriorating item with preservation technology under selling price and trade credit dependent quadratic demand in a supply chain," *International Journal of Applied and Computational Mathematics*, vol. 3, no. 2, pp. 363–379, 2017.

[29] B. C. Giri, H. Pal, and T. Maiti, "A vendor-buyer supply chain model for time-dependent deteriorating item with preservation technology investment," *International Journal of Mathematics in Operational Research*, vol. 10, no. 4, pp. 431–449, 2017.

[30] X. Cai, J. Chen, Y. Xiao, and X. Xu, "Optimization and coordination of fresh product supply chains with freshness-keeping effort," *Production Engineering Research and Development*, vol. 19, no. 3, pp. 261–278, 2010.

[31] M. Yu and A. Nagurney, "Competitive food supply chain networks with application to fresh produce," *European Journal of Operational Research*, vol. 224, no. 2, pp. 273–282, 2013.

[32] Y.-C. Tsao, "Joint location, inventory, and preservation decisions for non-instantaneous deterioration items under delay in payments," *International Journal of Systems Science*, vol. 47, no. 3, pp. 572–585, 2016.

[33] Y.-C. Tsao, "Designing a supply chain network for deteriorating inventory under preservation effort and trade credits," *International Journal of Production Research*, vol. 54, no. 13, pp. 3837–3851, 2016.

[34] H. Rijgersberg, S. Tromp, L. Jacxsens, and M. Uyttendaele, "Modeling logistic performance in quantitative microbial risk assessment," *Risk Analysis*, vol. 30, no. 1, pp. 20–31, 2010.

[35] U. Derigs, J. Gottlieb, J. Kalkoff, M. Piesche, F. Rothlauf, and U. Vogel, "Vehicle routing with compartments: Applications, modelling and heuristics," *OR Spectrum*, vol. 33, no. 4, pp. 885–914, 2011.

[36] H. Grillo, M. M. E. Alemany, A. Ortiz, and V. S. Fuertes-Miquel, "Mathematical modelling of the order-promising process for fruit supply chains considering the perishability and subtypes of products," *Applied Mathematical Modelling*, vol. 49, pp. 255–278, 2017.

[37] F. Dabbene, P. Gay, and N. Sacco, "Optimisation of fresh-food supply chains in uncertain environments, Part I: Background and methodology," *Biosystems Engineering*, vol. 99, no. 3, pp. 348–359, 2008.

[38] O. Ahumada and J. R. Villalobos, "A tactical model for planning the production and distribution of fresh produce," *Annals of Operations Research*, vol. 190, pp. 339–358, 2011.

[39] F. Dabbene, P. Gay, and N. Sacco, "Optimisation of fresh-food supply chains in uncertain environments, Part II: A case study," *Biosystems Engineering*, vol. 99, no. 3, pp. 360–371, 2008.

[40] A. Rong and M. Grunow, "A methodology for controlling dispersion in food production and distribution," *OR Spectrum*, vol. 32, no. 4, pp. 957–978, 2010.

[41] X. Cai and X. Zhou, "Optimal policies for perishable products when transportation to export market is disrupted," *Production Engineering Research and Development*, vol. 23, no. 5, pp. 907–923, 2014.

[42] M. Ketzenberg and M. E. Ferguson, "Managing slow-moving perishables in the grocery industry," *Production Engineering Research and Development*, vol. 17, no. 5, pp. 513–521, 2008.

[43] B. Bilgen and H.-O. Günther, "Integrated production and distribution planning in the fast moving consumer goods industry: A block planning application," *OR Spectrum*, vol. 32, no. 4, pp. 927–955, 2010.

[44] M. Soysal, J. M. Bloemhof-Ruwaard, R. Haijema, and J. G. A. J. van der Vorst, "Modeling a green inventory routing problem for perishable products with horizontal collaboration," *Computers & Operations Research*, 2016.

[45] A. Rong, R. Akkerman, and M. Grunow, "An optimization approach for managing fresh food quality throughout the supply chain," *International Journal of Production Economics*, vol. 131, no. 1, pp. 421–429, 2011.

[46] P. Farahani, M. Grunow, and H.-O. Günther, "Integrated production and distribution planning for perishable food products," *Flexible Services and Manufacturing Journal*, vol. 24, no. 1, pp. 28–51, 2012.

[47] D. Adelman and A. J. Mersereau, "Dynamic capacity allocation to customers who remember past service," *Management Science*, vol. 59, no. 3, pp. 592–612, 2013.

[48] L. C. Coelho and G. Laporte, "Optimal joint replenishment, delivery and inventory management policies for perishable products," *Computers & Operations Research*, vol. 47, pp. 42–52, 2014.

[49] P. Devapriya, W. Ferrell, and N. Geismar, "Integrated production and distribution scheduling with a perishable product," *European Journal of Operational Research*, vol. 259, no. 3, pp. 906–916, 2017.

[50] H. Liu, J. Zhang, C. Zhou, and Y. Ru, "Optimal purchase and inventory retrieval policies for perishable seasonal agricultural products," *OMEGA - The International Journal of Management Science*, 2017.

[51] Y. Qiu, J. Qiao, and P. M. Pardalos, "Optimal production, replenishment, delivery, routing and inventory management policies for products with perishable inventory," *Omega* , 2018.

[52] S. Makkar, P. C. Jha, and N. Arora, "Single-source, single-destination coordination of EOQ model for perishable products with quantity discounts incorporating partial/full truckload policy under fuzzy environment," *Advances in Intelligent and Soft Computing*, vol. 130, no. 1, pp. 971–982, 2012.

[53] X. Cai, J. Chen, Y. Xiao, X. Xu, and G. Yu, "Fresh-product supply chain management with logistics outsourcing," *OMEGA - The International Journal of Management Science*, vol. 41, no. 4, pp. 752–765, 2013.

[54] M. Rahdar and A. S. Nookabadi, "Coordination mechanism for a deteriorating item in a two-level supply chain system," *Applied Mathematical Modelling*, vol. 38, no. 11-12, pp. 2884–2900, 2014.

[55] R. Uthayakumar and S. Priyan, "Pharmaceutical supply chain and inventory management strategies: optimization for a pharmaceutical company and a hospital," *Operations Research for Health Care*, vol. 2, no. 3, pp. 52–64, 2013.

[56] T. Jia, X. Li, N. Wang, and R. Li, "Integrated inventory routing problem with quality time windows and loading cost for deteriorating items under discrete time," *Mathematical Problems in Engineering*, vol. 2014, Article ID 537409, 2014.

[57] A. Diabat, T. Abdallah, and T. Le, "A hybrid tabu search based heuristic for the periodic distribution inventory problem with perishable goods," *Annals of Operations Research*, vol. 242, no. 2, pp. 373–398, 2016.

[58] S. Lee and D. Kim, "An optimal policy for a single-vendor single-buyer integrated production-distribution model with both deteriorating and defective items," *International Journal of Production Economics*, vol. 147, pp. 161–170, 2014.

[59] M. Gaggero and F. Tonelli, "Optimal control of distribution chains for perishable goods," *IFAC-PapersOnLine*, vol. 28, no. 3, pp. 1049–1054, 2015.

[60] M. A. F. Belo-Filho, P. Amorim, and B. Almada-Lobo, "An adaptive large neighbourhood search for the operational integrated production and distribution problem of perishable products," *International Journal of Production Research*, vol. 53, no. 20, pp. 6040–6058, 2015.

[61] S. Priyan and R. Uthayakumar, "An integrated production-distribution inventory system for deteriorating products involving fuzzy deterioration and variable setup cost," *Journal of Industrial and Production Engineering*, vol. 31, no. 8, pp. 491–503, 2014.

[62] S. M. Seyedhosseini and S. M. Ghoreyshi, "An integrated model for production and distribution planning of perishable products with inventory and routing considerations," *Mathematical Problems in Engineering*, vol. 2014, Article ID 475606, 2014.

[63] S. M. Seyedhosseini and S. M. Ghoreyshi, "Integration of production and distribution decisions of perishable products considering feasible delivery routes," *International Journal of Applied Management Science*, vol. 6, no. 3, pp. 267–284, 2014.

[64] S. M. Seyedhosseini and S. M. Ghoreyshi, "An integrated production and distribution planning model for perishable products," *International Journal of Operational Research*, vol. 23, no. 3, pp. 268–283, 2015.

[65] C. Sel, B. Bilgen, J. M. Bloemhof-Ruwaard, and J. G. A. J. van der Vorst, "Multi-bucket optimization for integrated planning and scheduling in the perishable dairy supply chain," *Computers & Chemical Engineering*, vol. 77, pp. 59–73, 2015.

[66] S. Mirzaei and A. Seifi, "Considering lost sale in inventory routing problems for perishable goods," *Computers & Industrial Engineering*, vol. 87, pp. 213–227, 2015.

[67] Z. Drezner and C. H. Scott, "Location of a distribution center for a perishable product," *Mathematical Methods of Operations Research*, vol. 78, no. 3, pp. 301–314, 2013.

[68] A. Dobhan and M. Oberlaender, "Hybrid contracting within multi-location networks," *International Journal of Production Economics*, vol. 143, no. 2, pp. 612–619, 2013.

[69] Z. Firoozi, N. Ismail, S. Ariafar, S. H. Tang, M. K. A. M. Ariffin, and A. Memariani, "Distribution network design for fixed lifetime perishable products: A model and solution approach," *Journal of Applied Mathematics*, vol. 2013, Article ID 891409, 2013.

[70] Z. Firoozi, N. Ismail, and S. Ariafar, "Effects of integration on the cost reduction in distribution network design for perishable products," *Mathematical Problems in Engineering*, vol. 2014, Article ID 739741, 10 pages, 2014.

[71] Z. Firoozi and S. Ariafar, "A supply chain network design model for random-lifetime products," *Journal of Industrial and Production Engineering*, vol. 34, no. 2, pp. 113–123, 2017.

[72] M. A. Dulebenets, E. E. Ozguven, R. Moses, and M. B. Ulak, "Intermodal Freight Network Design for Transport of Perishable Products," *Open Journal of Optimization*, vol. 05, no. 04, pp. 120–139, 2016.

[73] S. Rashidi, A. Saghaei, S. J. Sadjadi, and S. Sadi-Nezhad, "Optimizing supply chain network design with location-inventory decisions for perishable items: A Pareto-based MOEA approach," *Scientia Iranica*, vol. 23, no. 6, pp. 3035–3045, 2016.

[74] M. de Keizer, R. Akkerman, M. Grunow, J. M. Bloemhof, R. Haijema, and J. G. van der Vorst, "Logistics network design

for perishable products with heterogeneous quality decay," *European Journal of Operational Research*, vol. 262, no. 2, pp. 535–549, 2017.

[75] M. E. Ferguson and O. Koenigsberg, "How should a firm manage deteriorating inventory?" *Production Engineering Research and Development*, vol. 16, no. 3, pp. 306–321, 2007.

[76] J. Blackburn and G. Scudder, "Supply chain strategies for perishable products: the case of fresh produce," *Production Engineering Research and Development*, vol. 18, no. 2, pp. 129–137, 2009.

[77] A. Sainathan, "Pricing and replenishment of competing perishable product variants under dynamic demand substitution," *Production Engineering Research and Development*, vol. 22, no. 5, pp. 1157–1181, 2013.

[78] X. Wang and D. Li, "A dynamic product quality evaluation based pricing model for perishable food supply chains," *Omega* , vol. 40, no. 6, pp. 906–917, 2012.

[79] B. Adenso-Díaz, S. Lozano, and A. Palacio, "Effects of dynamic pricing of perishable products on revenue and waste," *Applied Mathematical Modelling*, vol. 45, pp. 148–164, 2016.

[80] A. Herbon, E. Levner, and T. C. E. Cheng, "Perishable inventory management with dynamic pricing using time-temperature indicators linked to automatic detecting devices," *International Journal of Production Economics*, vol. 147, pp. 605–613, 2014.

[81] A. Herbon and E. Khmelnitsky, "Optimal dynamic pricing and ordering of a perishable product under additive effects of price and time on demand," *European Journal of Operational Research*, vol. 260, no. 2, pp. 546–556, 2017.

[82] E. P. Chew, C. Lee, R. Liu, K.-S. Hong, and A. Zhang, "Optimal dynamic pricing and ordering decisions for perishable products," *International Journal of Production Economics*, vol. 157, no. 1, pp. 39–48, 2014.

[83] X. Chen, Z. Pang, and L. Pan, "Coordinating inventory control and pricing strategies for perishable products," *Operations Research*, vol. 62, no. 2, pp. 284–300, 2014.

[84] A. Herbon, "Optimal two-level piecewise-constant price discrimination for a storable perishable product," *International Journal of Production Research*, 2015.

[85] P. Hu, S. Shum, and M. Yu, "Joint inventory and markdown management for perishable goods with strategic consumer behavior," *Operations Research*, vol. 64, no. 1, pp. 118–134, 2016.

[86] Q. Li, P. Yu, and X. Wu, "Managing perishable inventories in retailing: replenishment, clearance sales, and segregation," *Operations Research*, vol. 64, no. 6, pp. 1270–1284, 2016.

[87] Y. Akçay, H. P. Natarajan, and S. H. Xu, "Joint dynamic pricing of multiple perishable products under consumer choice," *Management Science*, vol. 56, no. 8, pp. 1345–1361, 2010.

[88] G. Gallego and M. Hu, "Dynamic pricing of perishable assets under competition," *Management Science*, vol. 60, no. 5, pp. 1241–1259, 2014.

[89] A. Herbon, "Dynamic pricing vs. acquiring information on consumers heterogeneous sensitivity to product freshness," *International Journal of Production Research*, vol. 52, no. 3, pp. 918–933, 2014.

[90] A. Herbon, "Optimal piecewise-constant price under heterogeneous sensitivity to product freshness," *International Journal of Production Research*, vol. 54, no. 2, pp. 365–385, 2016.

[91] A. Herbon, "Should retailers hold a perishable product having different ages? The case of a homogeneous market and multiplicative demand model," *International Journal of Production Economics*, vol. 193, pp. 479–490, 2017.

[92] A. Herbon, "Optimal Pricing and Replenishment of an Expiring Inventoried Product under Heterogeneous Consumer Sensitivities," *Decision Sciences*, 2017.

[93] A. Herbon, "Potential additional profits of selling a perishable product due to implementing price discrimination versus implementation costs," *International Transactions in Operational Research*, 2017.

[94] B. A. Pasternack, "Optimal pricing and return policies for perishable commodities," *Marketing Science*, vol. 27, no. 1, pp. 133–140, 2008.

[95] Y. Li, A. Lim, and B. Rodrigues, "Pricing and inventory control for a perishable product," *Manufacturing and Service Operations Management*, vol. 11, no. 3, pp. 538–542, 2009.

[96] Y. Li, B. Cheang, and A. Lim, "Grocery perishables management," *Production Engineering Research and Development*, vol. 21, no. 3, pp. 504–517, 2012.

[97] L.-M. Chen and A. Sapra, "Joint inventory and pricing decisions for perishable products with two-period lifetime," *Naval Research Logistics (NRL)*, vol. 60, no. 5, pp. 343–366, 2013.

[98] Y. T. Chung and F. Erhun, "Designing supply contracts for perishable goods with two periods of shelf life," *Institute of Industrial Engineers (IIE). IIE Transactions*, vol. 45, no. 1, pp. 53–67, 2013.

[99] O. Kaya and A. L. Polat, "Coordinated pricing and inventory decisions for perishable products," *OR Spectrum*, vol. 39, no. 2, pp. 589–606, 2017.

[100] J. Chen, M. Dong, Y. Rong, and L. Yang, "Dynamic pricing for deteriorating products with menu cost," *OMEGA - The International Journal of Management Science*, 2015.

[101] G. A. Chua, R. Mokhlesi, and A. Sainathan, "Optimal Discounting and Replenishment Policies for Perishable Products," *International Journal of Production Economics*, vol. 186, pp. 8–20, 2017.

[102] I.-H. Hong, J.-F. Dang, Y.-H. Tsai et al., "An RFID application in the food supply chain: A case study of convenience stores in Taiwan," *Journal of Food Engineering*, vol. 106, no. 2, pp. 119–126, 2011.

[103] K. M. Karlsen, B. Dreyer, P. Olsen, and E. O. Elvevoll, "Literature review: Does a common theoretical framework to implement food traceability exist?" *Food Control*, vol. 32, no. 2, pp. 409–417, 2013.

[104] T. Bosona and G. Gebresenbet, "Food traceability as an integral part of logistics management in food and agricultural supply chain," *Food Control*, vol. 33, no. 1, pp. 32–48, 2013.

[105] C. Dupuy, V. Botta-Genoulaz, and A. Guinet, "Batch dispersion model to optimise traceability in food industry," *Journal of Food Engineering*, vol. 70, no. 3, pp. 333–339, 2005.

[106] X. Wang, D. Li, and C. O'Brien, "Optimisation of traceability and operations planning: an integrated model for perishable food production," *International Journal of Production Research*, vol. 47, no. 11, pp. 2865–2886, 2009.

[107] X. Wang, D. Li, C. O'brien, and Y. Li, "A production planning model to reduce risk and improve operations management," *International Journal of Production Economics*, vol. 124, no. 2, pp. 463–474, 2010.

[108] M. A. Resende-Filho and T. M. Hurley, "Information asymmetry and traceability incentives for food safety," *International Journal of Production Economics*, vol. 139, no. 2, pp. 596–603, 2012.

[109] S. Piramuthu, P. Farahani, and M. Grunow, "RFID-generated traceability for contaminated product recall in perishable food

supply networks," *European Journal of Operational Research*, vol. 225, no. 2, pp. 253–262, 2013.

[110] L. Comba, G. Belforte, F. Dabbene, and P. Gay, "Methods for traceability in food production processes involving bulk products," *Biosystems Engineering*, vol. 116, no. 1, pp. 51–63, 2013.

[111] M. S. Memon, Y. H. Lee, and S. I. Mari, "Analysis of Traceability Optimization and Shareholder's Profit for Efficient Supply Chain Operation under Product Recall Crisis," *Mathematical Problems in Engineering*, vol. 2015, Article ID 896239, 2015.

[112] L. Zhu, "Economic analysis of a traceability system for a two-level perishable food supply chain," *Sustainability*, vol. 9, no. 5, article no. 682, 2017.

[113] J. B. Dai, L. Fan, N. K. S. Lee, and J. Li, "Joint optimisation of tracking capability and price in a supply chain with endogenous pricing," *International Journal of Production Research*, vol. 55, no. 18, pp. 5465–5484, 2017.

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Research Article

Quality Risk Evaluation of the Food Supply Chain Using a Fuzzy Comprehensive Evaluation Model and Failure Mode, Effects, and Criticality Analysis

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Evaluating the quality risk level in the food supply chain can reduce quality information asymmetry and food quality incidents and promote nationally integrated regulations for food quality. In order to evaluate it, a quality risk evaluation indicator system for the food supply chain is constructed based on an extensive literature review in this paper. Furthermore, a mathematical model based on the fuzzy comprehensive evaluation model (FCEM) and failure mode, effects, and criticality analysis (FMECA) for evaluating the quality risk level in the food supply chain is developed. A computational experiment aimed at verifying the effectiveness and feasibility of this proposed model is conducted on the basis of a questionnaire survey. The results suggest that this model can be used as a general guideline to assess the quality risk level in the food supply chain and achieve the most important objective of providing a reference for the public and private sectors when making decisions on food quality management.

1. Introduction

In 2016, the State Council of the People's Republic of China issued guidelines on food safety work. These provisions emphasized improving the quality of edible agricultural products, strengthening risk prevention and control measures, promoting quality management throughout the food supply chain, and accelerating nationally integrated regulations for food safety. These guidelines highlight China's attention to quality risk management in the food supply chain [1].

Food quality is defined as the access of all people to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life [2, 3]. Food quality covers a broad area that can be characterized by a set of different risk factors [4–6], such as the agricultural conditions [7], production process [8], use of antimicrobials [9], and consumer demand [10, 11]. These factors can be represented by various indicators such as environmental pollution, microbial contamination, logistics, warehousing, and transportation. The risk indicators are related to the food supply chain processes [12] and can be evaluated and documented on the basis of imprecise inputs. The data of these processes are imprecise and difficult to quantify since they pertain to both the resilience of the food supply chain and the consumer demand and supply channels such as retail outlets and restaurants. Therefore, it is difficult to use traditional data-based approaches to evaluate food quality. Addressing this challenge requires the managers to develop some precise methods for assessing the risk level of all factors in every link of the food supply chain [13] and calculating them as a whole [14]. Unfortunately, few related studies have been done.

The quality risk level of food is defined as the potential hazard which is caused by unsafe practices in the food supply chain. The uncertainty of the ability to acquire safe foods is also called food insecurity and can be measured by the risk level of food quality [15]. And the quality risk level of food security is an important problem related to the food supply chain environment. One effective solution to solve this problem is to build an evaluation indicator system based on the fuzzy sets theory [16]. Several studies have considered that building the indicator system is the first step in assessing the quality risk, and many research results have been made, such as in the case of Wang et al. who developed an index system to evaluate the transparency of the supervision of food safety in China as a prerequisite for an accurate evaluation of the food safety risk level. Jie et al. analyzed the supply chain performance of Australian cattle producers based on food supply chain performance indicators [17]. Turi et al. proposed aggregate indicators to assess the performance of the food supply chain by considering economic, social, and environmental development [18]. Nilsson et al. proposed total quality indicators for the food production chain [19]. Salvo et al. focused on the toxic inorganic pollutants in foods from agricultural producing to evaluate the risks for consumers [20]. In these studies, however, the evaluation objects were only a single link not the whole food supply chain. Moreover, the food quality risk supervision at the national level is missed in these studies. Therefore, the existing literature cannot provide an effective guidance for the quality risk evaluation throughout the whole food supply chain, which means that a comprehensive and systematic study on the area of quality risk evaluation in the food supply chain is still missing.

Many affecting factors of the quality risk evaluation in the food supply chain exhibit highly fuzzy uncertainty and cannot be analyzed quantitatively. Therefore, it is difficult to evaluate the level of quality risk by a single, defined management criterion [21]. To address this fuzzy uncertainty problem, in 1965, Zadeh proposed the concept of fuzzy sets, which laid the foundation for the application of the fuzzy comprehensive evaluation model (FCEM) in risk management [22]. The FCEM is a method to evaluate fuzzy mathematics, which can transform a qualitative evaluation into a quantitative evaluation [23–25]. Combined with other methods, the greatest feature of the FCEM is that it can integrate the intuition and fuzziness of human thinking, thus circumventing the unity of results required by traditional mathematical methods [26]. Therefore, the FCEM has become an effective multifactor decision-making tool for comprehensive evaluations [27] and real-word problem solving in areas such as international relations [28], aircraft flight safety [29], swine building environment [23], health, safety, and environmental management [30], regional water resources capacity [31], and teaching performance [32]. Therefore, in this paper, an FCEM for modeling these uncertainties and assessing food quality risk level is developed to determine the overall food quality risk by monitoring various independent risk factors and indictors in the food supply chain.

The rest of this paper is structured as follows. Section 2 describes the construction of a quality risk evaluation indicator system that covers the whole food supply chain based on an extensive literature review. Section 3 proposes an FCEM for the quality risk evaluation of the food supply chain based on FCEM and FMECA. Section 4 verifies the effectiveness and feasibility of the model using a computational experiment, and Section 5 presents the conclusions.

2. Quality Risk Evaluation Indicator System for the Food Supply Chain

To ensure the accuracy and effectiveness, a quality risk evaluation indicator system that covers the entirety of the food supply chain should be established before evaluating food quality risk. Existing research on this system has been very limited. There is no ready-made quality risk evaluation indicator system for the food supply chain [13]. Here, the effective approach to establishing the preliminary indicator framework is to analyze the existing literature and the laws and regulations of food safety regulatory [58]. On this basis, the quality risk evaluation indicator system for the food supply chain can be built by the method which is based on the fuzzy analytic hierarchy process (FAHP) proposed by Wang et al. [59], shown as Table 1.

According to Table 1, the evaluation objects for quality risk of the food supply chain can be generalized into five categories: raw material supply risk [33–37]; production and processing risk [34, 37–42]; logistics, warehousing, and transportation risk [40–46]; sales and consumption risk [42, 47–51]; and government regulatory risk [52–57]. Raw material supply; production and processing; logistics, warehousing, and transportation; sales and consumption are the four different links of the food supply chain, while government regulations could affect every link of the food supply chain. The connotations of each evaluation object could be described as follows.

(1) Raw Material Supply Risk. The risk of raw material supply involves the raw materials produced by human pollution, natural pollution, and other factors that lead to pesticide residues, pathogen pollution, and illegal additives during the process of planting or breeding, which results in long-term or short-term harm to human health [34]. Raw material supply risk is a source of food quality risk, including soil pollution, air pollution, water pollution, heavy metal pollution, illegal use of additives, residual inputs, microbial contamination, pathogenic bacteria pollution, and transgenic technology risk.

(2) Production and Processing Risk. This risk arises when the safety management and production environment during the processes of production and packaging are not compliant with regulations; this risk could lead to possible food contamination and illegal additives and produce potential safety hazards to human health. As this link involves the food quality and safety in the whole food industrial chain, its impact is relatively large. The main quality risk evaluation indicators included in this link are illegal use of additives, contamination with foreign matter, inability to wash a food product clean, presence of detergent residue, pathogen contamination, microbial contamination, uncertified processing equipment, nonstandardized processing personnel operation, insufficient processing environment, insufficient processing equipment, inappropriate packaging, insufficient packaging quality, uncertified packaging logo, insufficient assurance of

Table 1: Quality risk evaluation indicator system for the food supply chain.

Evaluation objects	Risk evaluation indicators		References
Raw material supply risk	Soil pollution Water pollution Illegal use of additives Microbial contamination, Transgenic technology risk	Air pollution Heavy metal pollution Residual inputs Pathogenic bacteria pollution	[33–37]
Production and processing risk	Illegal use of additives Inability to wash a food product clean Pathogen contamination Uncertified processing equipment Insufficient processing environment Inappropriate packaging Uncertified packaging logo Quality inspection risk	Contamination with foreign matter Presence of detergent residue Microbial contamination Nonstandardized processing personnel operation Insufficient processing equipment Insufficient packaging quality Insufficient assurance of personnel health Insufficient storage process	[34, 37–42]
Logistics, warehousing, and transportation risk	Inventory control technology Transport vehicle sanitation Third-party logistics level Product portfolio storage transport Logistics road infrastructure Vehicle scheduling and monitoring information feedback	Intelligent temperature-control facilities Cold chain hardware supporting facilities Partner technology platform convergence Cold chain logistics information transmission Illegal operation of Logistics transport personnel	[40–46]
Sales and consumption risk	Selling expired food False reporting of food ingredients Poor sanitation conditions Poor sanitation in cooking facilities Insufficient storage environment	Falsifying the date of production Poor sanitation in dining establishments Improper disposal of waste food Improper eating methods	[42, 47–52]
Government regulatory risk	Imperfect regulatory system Supervisor moral hazard Regulatory organization Regulatory process management Regulatory detection technology	Supervisory staff level Supervision channels Regulatory agency efficiency Regulatory results feedback Other risks	[53–57]

personnel health, quality inspection risk, and insufficient storage process.

(3) Logistics, Warehousing, and Transportation Risk. The logistics, warehousing, and transportation risk involves the raw food materials and finished products containing harmful substances or being subject to pollution or deterioration during the process of transport or storage, which results in the existence of potential safety hazards. In this paper, logistics, warehousing, and transportation includes both the process from the raw materials to production and the process from the finished product to consumption. The indicators of this evaluation objective include inventory control technology, intelligent temperature-control facilities, transport vehicle sanitation, cold chain hardware supporting facilities, third-party logistics level, partner technology platform convergence, product portfolio storage transport, cold chain logistics information transmission, logistics road infrastructure, illegal operation of logistics transport personnel, vehicle scheduling, and monitoring information feedback.

(4) Sales and Consumption Risk. The sales and consumption risk involves food contamination, deterioration, and contamination with harmful substances due to expired shelf life, food fraud, improper sales environments, or improper consumption of food, which poses a potential hazard to human health. The quality risk evaluation indicators in this link include selling expired food, falsifying the date of production, false reporting of food ingredients, poor sanitation in dining establishments, poor sanitation conditions, improper disposal of waste food, poor sanitation in cooking facilities, improper eating methods, and insufficient storage environment.

(5) Government Regulatory Risk. In the food industry, manufacturers may add chemical additives to augment the appearance or the taste of food. This process may increase food demand and sales profits but cause health problems among consumers [53]. The government can take punitive measures to regulate such risky behavior and benefit from the tax income generated by the increased revenues arising from such additives. An analysis of the current status of China's food quality regulations reveals that the quality risk evaluation indicators regarding government regulation include imperfect regulatory system, supervisory staff level, supervisor moral hazard, supervision channels, regulatory organization regulatory, agency efficiency, regulatory process management, regulatory results feedback, and regulatory detection technology.

3. Evaluation Model

3.1. Fuzzy Comprehensive Evaluation Method. FCEM is a method based on the membership degree theory in fuzzy mathematics, which transform the qualitative evaluation into quantitative evaluation [27, 60, 61]. It has now become an effective multifactor decision-making tool for comprehensive evaluation. Combined with experts grading method, FCEM can make a full reflection on the fuzziness of evaluation criteria and the influence factors and produce evaluation results closer to the actual situation [62]. The typical FCEM process could be shown in Figure 1.

Shown as Figure 1, the typical process of FCEM could be divided into five stages; the main task in the 1st stage is to establish a scientific set of indicators which is determined by the situation of evaluation objective; this indicators set will lay the foundation for the application of FCEM. In the 2nd stage, the assessment comment set of evaluation objective and the criterion used to reflect the standard of scoring should be established and proposed; this will provide the data foundation for quantifying the results of assessment comment. Each element in the set of indicators makes a different contribution to the realization of risk assessment; the weights of these factors are important and different; therefore, in the 3rd stage, the weight matrixes which are determined by the contribution of the evaluation objective should be built and measured. There are many ways to build the weight matrix, such as analytic hierarchy process (AHP), entropy, and FMECA; the criterion for the selection of these methods is whether the proposed method could satisfy the characteristics and requirements of the evaluation objectives. In the 4th stage, a fuzzy comprehensive assessment matrix which could reflect the risk level of assessment objective should be established on the basis of the construction results of weight matrixes. Combined with the assessment comment set, the fuzzy comprehensive assessment matrix, the value of the whole, and each evaluation objective should be calculated in 5th stage, which will provide a reference for managers to make risk management decisions.

3.2. Construction of the Food Quality Risk Evaluation Model Using FCEM. The process of food quality risk evaluation in the food supply chain is a typical FCEM process. According to Section 3.1, using FCEM to evaluate the level of food quality risk in the food supply chain could be divided into five stages: (1) construct the food quality risk evaluation indicator set, (2) establish the food quality risk assessment comment set, (3) determine the weight matrix, (4) establish the comprehensive assessment matrix, and (5) finalize the FCEM [63].

In the first stage, construct a food quality risk evaluation indicator set Q, which is composed of the evaluation objects Q_i and their corresponding evaluation indicators Q_{ij}, shown as follows:

$$\begin{gathered} Q = \left\{ Q_1, Q_{\dots}, Q_i, Q_{\dots}, Q_n \right\}, \\ Q_i = \left\{ Q_{i1}, \dots, Q_{ij}, \dots, Q_{im} \right\} \\ \left(i = 1, 2, \dots, n;\ j = 1, 2, \dots, m \right), \end{gathered} \tag{1}$$

where Q is the food quality risk evaluation indicator set, n is the number of evaluation objects, Q_i $(i \in [0, n])$ is the ith evaluation object, Q_{ij} is the jth food quality risk evaluation indicator of Q_i, and m is the number of food quality risk evaluation indicators in Q_i.

In the second stage, establish the food quality risk assessment comment set $\mathscr{L}$ to describe the fuzzy logic relationship among different indicators. Here, $\mathscr{L}$ is a collection

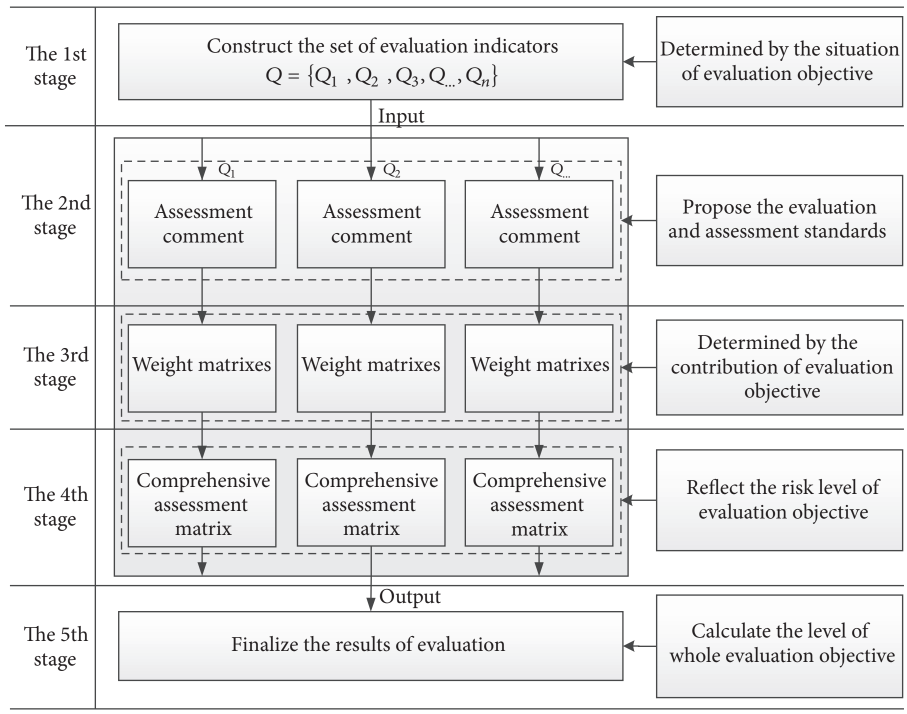

Figure 1: The application stage of FCEM.

of five comments used to evaluate the food quality risk level according to the criterion of the FCEM, shown as follows:

$$\mathscr{L} = \{\ell_1, \ell_2, \ell_3, \ell_4, \ell_5\}, \tag{2}$$

where $\mathscr{L}$ is the food quality risk assessment comment set and ℓ_1, ℓ_2, ℓ_3, ℓ_4, and ℓ_5 are the comments representing the food quality risk levels of "Terrible," "Unacceptable," "Fair," "Acceptable," and "Desirable." These levels are represented by scores of 1, 2, 3, 4, and 5. The risk assessment comment set $\mathscr{L}$ can be expressed as follows:

$$\mathscr{L} = \{1, 2, 3, 4, 5\}. \tag{3}$$

According to this criterion, the fuzzy comprehensive evaluation matrixes R and R_i $(i = 1, 2, \ldots, n)$ can be determined by

$$R_i = \begin{Bmatrix} r_{i11} & r_{i12} & r_{i13} & r_{i14} & r_{i15} \\ r_{i21} & r_{i22} & r_{i23} & r_{i24} & r_{i25} \\ r_{i31} & r_{i32} & r_{i33} & r_{i34} & r_{i35} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ r_{im1} & r_{im2} & r_{im3} & r_{im4} & r_{im5} \end{Bmatrix}, \tag{4}$$

where $R = \{R_1, R, \ldots, R_i\}$ and R_i $(i = 1, 2, \ldots, n)$ are the fuzzy comprehensive evaluation matrixes of Q and Q_i. r_{imk} $(k = 1, 2, 3, 4, 5)$ is the comment level of Q_{im}.

In the third stage, determine the weight matrixes W and W_i'. Different elements in sets Q and Q_i provide different contributions to the level of food quality risk. Thus, the weights of these indicators are different. The assessment index weights vector can be determined by

$$\begin{gathered} W = \{W_1, W_2, \ldots, W_i, \ldots, W_n\} \quad (i = 1, 2, \ldots, n), \\ W_i' = \{W_{i1}', W_{i2}', \ldots, W_{ij}', \ldots, W_{im}'\} \\ (i = 1, 2, \ldots, n;\ 1 \le j \le m), \\ \sum_{i=1}^{n} W_i = 1, \\ \sum_{j=1}^{m} W_{ij}' = 1, \end{gathered} \tag{5}$$

where W and W_i' are the weight vectors of food quality risk evaluation objects and indicators. W_i and W_{im}' are the weights of Q_i and Q_{im}. The values of W_i and W_{im}' can be calculated by the method of FMECA.

In the fourth stage, establish the comprehensive assessment matrix V to reflect the food quality risk level of each evaluation objective by

$$V = \mathrm{W} \circ \mathrm{X}^T, \tag{6}$$

$$X = (X_1, X_2, \ldots, X_i), \tag{7}$$

$$X_i = W_i' \times R_i, \tag{8}$$

where V is the fuzzy comprehensive assessment matrix that can reflect the food quality risk level of the evaluation objective, X_i is the fuzzy comprehensive assessment matrix of Q_i, and X is the fuzzy comprehensive assessment matrix set.

Finally, finalize the FCEM. Recording the food quality risk level and each evaluation objective as Y and Y', combined with $\mathscr{L}$, V, and X_i, the values of Y and Y' can be calculated by

$$\begin{aligned} Y &= \mathscr{L} \cdot V^T, \\ Y' &= (Y_1, Y_2, \ldots, Y_i), \\ Y_i &= \mathscr{L} \cdot X_i^T, \end{aligned} \tag{9}$$

where Y and Y_i are the food quality risk levels of Q and Q_i. Y' is the set of Q_is' food quality risk levels. According to (9), the food quality risk levels of Q and Q_i can be obtained.

3.3. Determinants of the Weight Vectors Using FMECA. According to Section 3.2, when applying the FCEM to evaluate the food quality risk level, the weight of indicator is very important. Generally, the weights of indicators during the application of the FCEM are usually given based on the experience of various experts, which leads to the limitation of subjectivity. To reduce this subjectivity, this paper takes the FMECA as the method to determine the weight vectors of evaluation indicators.

FMECA is a safety and reliability analysis tool, which has been widely used for the identification of system/process potential failures, their causes, and consequences. This method focuses on "discussions before system failure" per the notion that "prevention is better than cure" [64]. FMECA provides an appropriate method to determine the weights of the elements depending on the occurrences of food quality risk parameters, their severity, the detection, and ability to control or compensate for the loss after a failure [64]. According to the FMECA, the weights of the indicators can be calculated by

$$\begin{aligned} W_i'' &= \frac{O_i \times S_i \times D_i}{C_i}, \\ W_{ij}'' &= \frac{O_{ij} \times S_{ij} \times D_{ij}}{C_{ij}}, \\ W_i &= \frac{W_i''}{\sum_{i=1}^{n} W_i''}, \\ W_{ij} &= \frac{W_{ij}''}{\sum_{j=1}^{m} W_{ij}''}, \end{aligned} \tag{10}$$

where W_i'' is the cross-sectional area of the evaluation object Q_i and W_{ij}'' is the cross-sectional area of the evaluation indicator Q_{ij}. O_i is the occurrence probability of Q_i. S_i is the severity after the occurrence of Q_i. D_i is the likelihood of detection of Q_i, and C_i is the ability to control or compensate for the loss following the occurrence of Q_i. The values of O_i, S_i, D_i, and C_i can be obtained by the experts grading method (EGM), where $O_i \in [1, 5]$, $S_i \in [1, 5]$, $D_i \in [1, 5]$, and $C_i \in [1, 5]$. The principles of expert evaluation are shown as (11)–(14).

$$O_i = \begin{cases} 1 & \text{lowest probability} \\ 5 & \text{highest probability} \\ o_i & \text{otherwise,} \end{cases} \tag{11}$$

where $1 < o_i < 5$. The higher the value of o_i, the higher the probability of Q_i.

$$S_i = \begin{cases} 1 & \text{slightest severity} \\ 5 & \text{worst severity} \\ s_i & \text{otherwise,} \end{cases} \tag{12}$$

where $1 < s_i < 5$. The higher the value of s_i, the worse the severity after the occurrence of Q_i.

$$D_i = \begin{cases} 1 & \text{highest likelihood of detection} \\ 5 & \text{lowest likelihood of detection} \\ d_i & \text{otherwise,} \end{cases} \tag{13}$$

where $1 < d_i < 5$. The higher the value of d_i, the lower the likelihood of detection of Q_i.

$$C_i = \begin{cases} 1 & \text{most difficult to control or compensate for the loss} \\ 5 & \text{least difficult to control or compensate for the loss} \\ c_i & \text{otherwise,} \end{cases} \tag{14}$$

where $1 < c_i < 5$. The higher the value of h_i, the easier to control or compensate for the loss after the occurrence of Q_i.

According to (11)-(12), $W_i'' \in [0.2, 125]$and $W_{im}' \in [0.2, 125]$. Then, the weights of different elements W_i and W_{im} can be obtained after normalizing W_i'' and W_{im}' by (13)-(14).

4. Computational Experiment and Results

Henan is an important province of China, with a population of 107.22 million in 2017, accounting for 7.8% of China's total population. Thus, Henan plays an important role in China's food consumption. Food quality directly affects people's health and economic development; therefore, improving food quality and safety and making the food chain more ecofriendly are the development goals pursued by Henan Province. However, Henan is a large agricultural province; the food supply chain from farm to fork includes so many links such as raw material supply, production and processing, logistics, warehousing and transportation, and sales and consumption. In such a food supply chain, there are many risk factors that could affect the food quality level at each link. The probability of occurrences and the severity of each occurrence are uncertain; thus, identifying the risk factors and evaluating the risk level of each link in the food supply chain are the prerequisite for controlling the food quality.

This issue aligns with the problem addressed by the model proposed in this paper. Therefore, the food supply chain of the Henan Province (FSCHP) is taken as a computational experiment to introduce the process of food quality risk evaluation in order to verify the validity and effectiveness of the proposed model.

According to Table 1 and the process of risk evaluation described in Section 3.2, the risk evaluation indicator set of FSCHP Q can be constructed as shown in Table 2.

In Table 2, Q is the risk evaluation indicator set of FSCHP. n is the number of evaluation objects in Q, in which $n = 5$. Q_i ($i \in [1, n]$) is the ith evaluation object, Q_{ij} is the jth risk evaluation indicator of Q_i, and m is the number of risk evaluation indicators. As shown in Table 2, the number of FSCHP's risk evaluation indicators is

$$m = \begin{cases} 9, & i = 1 \\ 16, & i = 2 \\ 11, & i = 3 \\ 9, & i = 4 \\ 10, & i = 5. \end{cases} \tag{15}$$

According to the criterion of FCEM and (2), the risk assessment comment set of FSCHP $\mathscr{L}$ can be established, where $\mathscr{L} = \{\ell_1, \ell_2, \ell_3, \ell_4, \ell_5\} = \{1, 2, 3, 4, 5\}$. To aggregate the risk assessment comments of the FSCHP and establish the fuzzy comprehensive evaluation matrixes R and R_i ($i = 1, 2, \ldots, n$), a questionnaire survey was designed (shown as Appendix A). The objectives of this survey included five categories of respondents—farmers, food processing enterprises, logistics and warehousing enterprises, retailers and consumers, and government regulators—to ensure the accuracy of the survey results. A total of 1000 questionnaires were issued, and 898 were returned, which included 22 unfinished and 27 identical questionnaires; these 49 questionnaires were considered invalid according to the statistical principles. Thus, 849 questionnaires were considered valid and completed questionnaires. The recovery rate and the valid questionnaire rate were 89.8% and 84.9%. Therefore, the results of this survey are robust and effective and thus can be used for further analyses.

According to the results of the assessment comments of the risk evaluation indicators, the fuzzy comprehensive evaluation matrixes of evaluation objects Q can be constructed. Here, this paper takes the evaluation object Q_2 (Q_2 was selected because the number of risk evaluation indicators of Q_2 is the highest) as an example to introduce the calculation process of the fuzzy comprehensive evaluation matrix R_2.

By analyzing the results of the survey questionnaires, the assessment comment of evaluation objective Q_2 can be obtained, as shown in Table 3.

In Table 3, the level of comment of risk evaluation indicator Q_{im} can be calculated by $r_{imk} = \text{Frequency}(Q_{imp_\alpha}) / \sum_{\alpha=1}^{5} \text{Frequency}(Q_{imp_\alpha})$, where $\text{Frequency}(Q_{imp_\alpha})$ is the number of times that the objectives of this questionnaire survey scored Q_{im} as p_α (α = 1, 2, 3, 4 or 5). Then, the fuzzy comprehensive evaluation matrix R_2 can be established as follows:

$$R_2 = \begin{bmatrix} r_{211} & r_{212} & \cdots & r_{215} \\ r_{221} & r_{222} & \cdots & r_{225} \\ r_{231} & r_{232} & \cdots & r_{235} \\ \cdots & \cdots & \cdots & \cdots \\ r_{2m1} & r_{2m2} & \cdots & r_{2m5} \end{bmatrix}$$
$$= \begin{bmatrix} 0.065 & 0.225 & 0.337 & 0.273 & 0.100 \\ 0.094 & 0.243 & 0.360 & 0.235 & 0.069 \\ 0.096 & 0.283 & 0.382 & 0.168 & 0.071 \\ 0.085 & 0.232 & 0.342 & 0.255 & 0.087 \\ 0.047 & 0.200 & 0.306 & 0.284 & 0.163 \\ 0.045 & 0.236 & 0.335 & 0.266 & 0.118 \\ 0.065 & 0.232 & 0.349 & 0.268 & 0.087 \\ 0.071 & 0.245 & 0.357 & 0.259 & 0.067 \\ 0.067 & 0.236 & 0.333 & 0.277 & 0.087 \\ 0.087 & 0.272 & 0.362 & 0.233 & 0.047 \\ 0.243 & 0.312 & 0.275 & 0.126 & 0.045 \\ 0.249 & 0.298 & 0.268 & 0.135 & 0.049 \\ 0.174 & 0.229 & 0.340 & 0.168 & 0.089 \\ 0.176 & 0.285 & 0.284 & 0.182 & 0.073 \\ 0.185 & 0.236 & 0.280 & 0.199 & 0.100 \\ 0.214 & 0.241 & 0.355 & 0.108 & 0.082 \end{bmatrix}. \tag{16}$$

Similarly, the fuzzy comprehensive evaluation matrix of the other evaluation objects R_1, R_3, R_4, and R_5 can be established as follows:

$$R_1 = \begin{bmatrix} 0.056 & 0.225 & 0.346 & 0.224 & 0.149 \\ 0.232 & 0.310 & 0.275 & 0.088 & 0.096 \\ 0.122 & 0.283 & 0.384 & 0.090 & 0.120 \\ 0.241 & 0.310 & 0.277 & 0.079 & 0.094 \\ 0.220 & 0.289 & 0.317 & 0.077 & 0.098 \\ 0.065 & 0.236 & 0.344 & 0.215 & 0.140 \\ 0.118 & 0.274 & 0.386 & 0.095 & 0.127 \\ 0.038 & 0.238 & 0.360 & 0.217 & 0.147 \\ 0.053 & 0.205 & 0.271 & 0.277 & 0.194 \end{bmatrix},$$

Table 2: Risk evaluation indicator set of FSCHP Q.

Evaluation object Q_i	Risk evaluation indicators Q_{ij}	
Raw material supply risk Q_1	Soil pollution Q_{11}	Air pollution Q_{12}
	Water pollution Q_{13}	Heavy metal pollution Q_{14}
	Illegal use of additives Q_{15}	Residual inputs Q_{16}
	Microbial contamination Q_{17}	Pathogenic bacteria pollution Q_{18}
	Transgenic technology risk Q_{19}	
Production and processing risk Q_2	Illegal use of additives Q_{21}	Contamination with foreign matter Q_{22}
	Inability to wash a food product clean Q_{23}	Presence of detergent residue Q_{24}
	Pathogen contamination Q_{25}	Microbial contamination Q_{26}
	Uncertified processing equipment Q_{27}	Nonstandardized processing personnel operation Q_{28}
	Insufficient processing environment Q_{29}	Insufficient processing equipment Q_{210}
	Inappropriate packaging Q_{211}	Insufficient packaging quality Q_{212}
	Uncertified packaging logo Q_{213}	Insufficient assurance of personnel health Q_{214}
	Quality inspection risk Q_{215}	Insufficient storage process Q_{216}
Logistics, warehousing, and transportation risk Q_3	Inventory control technology Q_{31}	Intelligent temperature-control facilities Q_{32}
	Transport vehicle sanitation Q_{33}	Cold chain hardware supporting facilities Q_{34}
	Third-party logistics level Q_{35}	Partner technology platform convergence Q_{36}
	Product portfolio storage transport Q_{37}	Cold chain logistics information transmission Q_{38}
	Logistics road infrastructure Q_{39}	Illegal operation of logistics transport personnel Q_{310}
	Vehicle scheduling and monitoring information feedback Q_{311}	
Sales and consumption risk Q_4	Selling expired food Q_{41}	Falsifying the date of production Q_{42}
	False reporting of food ingredients Q_{43}	Poor sanitation in dining establishments Q_{44}
	Poor sanitation conditions Q_{45}	Improper disposal of waste food Q_{46}
	Poor sanitation in cooking facilities Q_{47}	Improper eating methods Q_{48}
	Insufficient storage environment Q_{49}	
Government regulatory risk Q_5	Imperfect regulatory system Q_{51}	Supervisory staff level Q_{52}
	Supervisor moral hazard Q_{53}	Supervision channels Q_{54}
	Regulatory organization Q_{55}	Regulatory agency efficiency Q_{56}
	Regulatory process management Q_{57}	Regulatory results feedback Q_{58}
	Regulatory detection technology Q_{59}	Other risks Q_{510}

Table 3: Assessment comment of evaluation objective Q_2.

Risk evaluation indicators	Frequency	Comment	P_1	P_2	P_3	P_4	P_5
Production and processing risk Q_2							
Illegal use of additives Q_{21}			58	202	303	245	90
Contamination with foreign matter Q_{22}			84	218	323	211	62
Inability to wash a food product clean Q_{23}			86	254	343	151	64
Presence of detergent residue Q_{24}			76	208	307	229	78
Pathogen contamination Q_{25}			42	180	275	255	146
Microbial contamination Q_{26}			40	212	301	239	106
Uncertified processing equipment Q_{27}			58	208	313	241	78
Nonstandardized processing personnel operation Q_{28}			64	220	321	233	60
Insufficient processing environment Q_{29}			60	212	299	249	78
Insufficient processing equipment Q_{210}			78	244	325	209	42
Inappropriate packaging Q_{211}			218	280	247	113	40
Insufficient packaging quality Q_{212}			224	268	241	121	44
Uncertified packaging logo Q_{213}			156	206	305	151	80
Insufficient assurance of personnel health Q_{214}			158	256	255	163	66
Quality inspection risk Q_{215}			166	212	251	179	90
Insufficient storage process Q_{216}			192	216	319	97	74

$$R_3 = \begin{bmatrix} 0.105 & 0.134 & 0.311 & 0.253 & 0.198 \\ 0.114 & 0.220 & 0.324 & 0.190 & 0.151 \\ 0.067 & 0.176 & 0.237 & 0.313 & 0.207 \\ 0.127 & 0.247 & 0.322 & 0.175 & 0.129 \\ 0.120 & 0.23 & 0.326 & 0.186 & 0.145 \\ 0.116 & 0.227 & 0.326 & 0.175 & 0.156 \\ 0.176 & 0.247 & 0.297 & 0.146 & 0.134 \\ 0.096 & 0.209 & 0.317 & 0.210 & 0.167 \\ 0.105 & 0.209 & 0.322 & 0.202 & 0.163 \\ 0.203 & 0.256 & 0.239 & 0.170 & 0.131 \\ 0.038 & 0.238 & 0.360 & 0.219 & 0.145 \end{bmatrix},$$

$$R_4 = \begin{bmatrix} 0.067 & 0.232 & 0.358 & 0.268 & 0.080 \\ 0.047 & 0.203 & 0.306 & 0.284 & 0.160 \\ 0.076 & 0.234 & 0.342 & 0.262 & 0.087 \\ 0.145 & 0.321 & 0.291 & 0.175 & 0.069 \\ 0.071 & 0.243 & 0.367 & 0.259 & 0.069 \\ 0.069 & 0.238 & 0.329 & 0.277 & 0.087 \\ 0.040 & 0.214 & 0.362 & 0.280 & 0.105 \\ 0.042 & 0.225 & 0.335 & 0.277 & 0.120 \\ 0.022 & 0.194 & 0.268 & 0.326 & 0.189 \end{bmatrix},$$

$$R_5 = \begin{bmatrix} 0.062 & 0.236 & 0.346 & 0.271 & 0.085 \\ 0.151 & 0.261 & 0.353 & 0.168 & 0.067 \\ 0.069 & 0.234 & 0.331 & 0.280 & 0.087 \\ 0.049 & 0.176 & 0.373 & 0.326 & 0.076 \\ 0.145 & 0.292 & 0.277 & 0.222 & 0.065 \\ 0.047 & 0.241 & 0.360 & 0.206 & 0.147 \\ 0.045 & 0.243 & 0.369 & 0.188 & 0.156 \\ 0.120 & 0.272 & 0.389 & 0.092 & 0.127 \\ 0.116 & 0.267 & 0.391 & 0.092 & 0.134 \\ 0.045 & 0.216 & 0.355 & 0.235 & 0.149 \end{bmatrix}. \tag{17}$$

Weight vectors are very important in determining the food quality risk level and can be calculated by FMECA according to Section 3.3. To calculate the weights of evaluation objects and risk indicators, five experts on food quality risk management were invited to score the values of O_i, S_i, D_i, and C_i with the principles of (11)–(14) (the scoring table is shown in Appendix B). The scoring results of the evaluation objects are shown in Table 4. Taking the average as the final score, the weights of evaluation objects W_i can be obtained according to (10):

$$\begin{aligned} W &= [W_1, W_2, W_3, W_4, W_5] \\ &= [0.0925, 0.191, 0.243, 0.284, 0.190]. \end{aligned} \tag{18}$$

Similarly, the weights of risk evaluation indicator W_i' can be calculated:

$$
\begin{aligned}
W_1' &= \left[W_{11}', \dots, W_{19}'\right] = [0.119, 0.143, 0.106, 0.104, 0.180, 0.060, 0.136, 0.092, 0.060]\,, \\
W_2' &= \begin{bmatrix} W_{21}', \dots, W_{28}', \\ W_{29}', \dots, W_{216}' \end{bmatrix} = \begin{bmatrix} 0.050, 0.133, 0.158, 0.033, 0.041, 0.027, 0.052, 0.055, \\ 0.031, 0.037, 0.075, 0.035, 0.065, 0.063, 0.042, 0.102 \end{bmatrix}, \\
W_3' &= \left[W_{31}', \dots, W_{311}'\right] = [0.044, 0.089, 0.049, 0.086, 0.165, 0.186, 0.063, 0.177, 0.055, 0.025, 0.059]\,, \\
W_4' &= \left[W_{41}', \dots, W_{412}'\right] = [0.152, 0.085, 0.055, 0.184, 0.162, 0.086, 0.054, 0.065, 0.156]\,, \\
W_5' &= \left[W_{51}', \dots, W_{510}'\right] = [0.124, 0.149, 0.090, 0.078, 0.053, 0.123, 0.048, 0.148, 0.104, 0.083]\,.
\end{aligned} \tag{19}
$$

According to (8), the fuzzy comprehensive assessment matrix of evaluation objects can be calculated:

$$
\begin{aligned}
X_1 &= [0.144, 0.271, 0.330, 0.133, 0.122]\,, \\
X_2 &= [0.128, 0.255, 0.338, 0.200, 0.079]\,, \\
X_3 &= [0.112, 0.219, 0.317, 0.197, 0.155]\,, \\
X_4 &= [0.071, 0.241, 0.322, 0.262, 0.105]\,, \\
X_5 &= [0.089, 0.246, 0.359, 0.198, 0.108]\,.
\end{aligned} \tag{20}
$$

According to (6)-(7), the fuzzy comprehensive assessment matrix V can be established:

$$
\begin{aligned}
V &= W \circ X^T = W \circ \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} \\
&= \begin{bmatrix} 0.0925 & 0.191 & 0.243 & 0.284 & 0.190 \end{bmatrix} \\
&\quad \circ \begin{bmatrix} 0.144 & 0.271 & 0.330 & 0.133 & 0.122 \\ 0.128 & 0.255 & 0.338 & 0.200 & 0.079 \\ 0.112 & 0.219 & 0.317 & 0.197 & 0.155 \\ 0.071 & 0.241 & 0.322 & 0.262 & 0.105 \\ 0.089 & 0.246 & 0.359 & 0.198 & 0.108 \end{bmatrix} \\
&= \begin{bmatrix} 0.206 & 0.214 & 0.215 & 0.225 & 0.219 \end{bmatrix}.
\end{aligned} \tag{21}
$$

According to (9), the level of FSCHP's food quality risk Y and the level of evaluation objects Y_i can be calculated:

$$
\begin{aligned}
Y &= \mathscr{L} \cdot V^T = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \end{bmatrix} \cdot \begin{bmatrix} 0.206 \\ 0.214 \\ 0.215 \\ 0.225 \\ 0.219 \end{bmatrix} = 3.273, \\
Y_1 &= \mathscr{L} \cdot {X_1}^T = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \end{bmatrix} \cdot \begin{bmatrix} 0.144 \\ 0.271 \\ 0.330 \\ 0.133 \\ 0.122 \end{bmatrix} = 2.819, \\
Y_2 &= 2.847, \\
Y_3 &= 3.065, \\
Y_4 &= 3.089, \\
Y_5 &= 2.990.
\end{aligned} \tag{22}
$$

The food quality risk levels of evaluation objects are shown in Figure 2.

According to the calculation results, the risk level of FSCHP's food quality Y is 3.273. This means that the risk level of FSCHP is much higher than the average level of risk comments of 2.5, more than 30.29%; it indicates that the risk level of FSCHP's food quality is relatively higher and requires scientific management in the process of supply chain management.

In Figure 2, the value of FSCHP's food quality risk assessment in descending order is sales and consumption risk Q_4; logistics, warehousing, and transportation risk Q_3; government regulatory risk Q_5; production and processing risk Q_2; raw material supply risk Q_1. Comparing the calculation results, the conclusion that the risk levels of sales and consumption risk Q_4 and logistics, warehousing and transportation risk Q_3, which are similar and equal to 3.09 and 3.06, are the highest two of the risk evaluation of FSCHP could be obtained. Meanwhile, the values of other indictors in FSCHP's quality risk Q_5, Q_2, and Q_1 which are equal to 2.99, 2.85, and 2.82 can be also obtained; these values are 3.25%,

Table 4: Values of O_i, S_i, D_i, and C_i scored by five experts.

Q		Scored by 1st expert					Scored by 2nd expert					Scored by 3rd expert					Scored by 4th expert					Scored by 5th expert					Average
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
	O				√				√						√				√					√			
	S			√						√					√					√				√			
Q_1	D	√					√							√				√					√				
	C				√					√					√						√			√			
	W_1''			3					3					12					2.4					6			5.28
	O			√							√				√				√				√				
	S					√			√						√					√						√	
Q_2	D		√					√						√				√						√			
	C				√			√							√				√					√			
	W_2''			7.5					15					12					10					10			10.90
	O				√					√		√							√						√		
	S			√						√					√					√				√			
Q_3	D		√								√					√		√					√				
	C				√				√					√			√						√				
	W_3''			6					26.67					6.67					6					24			13.87
	O		√						√							√			√					√			
	S				√					√				√							√				√		
Q_4	D					√					√		√							√					√		
	C				√				√				√						√					√			
	W_4''			10					20					15					20					16			16.20
	O		√							√		√								√				√			
	S				√						√				√			√								√	
Q_5	D					√			√							√					√		√				
	C				√				√					√						√					√		
	W_5''			10					20					6.67					10					7.5			10.83

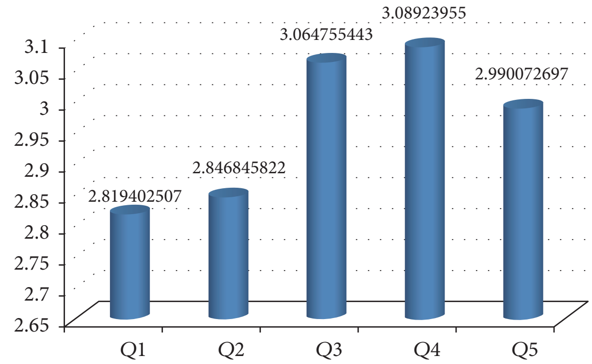

Figure 2: Food quality risk levels of evaluation objects.

7.77%, and 8.74% lower than the highest evaluation object Q_4. Analyzing this phenomenon, we can find that the reason why the risk levels of sales and consumption risk and the logistics, warehousing, and transportation risk are the highest is because there are too many uncontrollable factors such as cold chain hardware supporting facilities, cold chain logistics information transmission, poor sanitation in cooking facilities, and poor sanitation in dining establishments existing in these management processes, and the standard of them is missing or implemented poorly or supervised poorly. The results are consistent with the actual situation of the FSCHP. Therefore, if managers want to control the food quality risk of the FSCHP effectively, sales and consumption and the logistics, warehousing, and transportation are the key factors that should be addressed first. What is more, seen from Figure 2, we can find that the raw material supply risk Q_1 in FSCHP is the lowest, which is because Henan is one of the largest agricultural provinces in China, and in order to improve the food quality, the standardized food cultivation model has been promoted and accepted by all farmers, which makes a great contribution to achieving the goal of controlling the food quality from its source [65].

Through the statistical analysis of the existing literature, it can be found that a lot of studies have been carried out to explore food quality in the food supply chain, such as Fearne, Hornibrook, and Dedman who conducted two exploratory case studies of retailer-led quality assurance schemes (QAS) for beef in Germany and Italy and found that QAS have the potential to reduce perceived risk and increase consumer confidence in specific fresh beef products [66]; Ting et al. took the quality sustainability in the food supply chain as research object and proposed a supply chain quality sustainability decision support system to support managers in food manufacturing firms to define good logistics plans in order to maintain the quality and safety of food products [67]; Chen et al. presented a mutually supporting analytical model and exploratory case to study the managerial and policy issues related to quality control in food supply chain management with a focus on the Chinese dairy industry and discussed numbers of important managerial and policy insights and implications in managing the global food supply chain quality and risk [68]. These studies and findings have already provided a valid reference for controlling the food quality in the supply chain food; however, many of them are focused on the quality or risk control in a single link [66, 67] or some independent aspects [68] in the food supply chain, which could only provide a basis for the quality and risk management of the single or independent aspect not the whole food supply chain. Compared with these literatures, the evaluation model proposed in our paper based on the FCEM and FMECA can be used as a general guideline to assess the quality risk level of the food supply chain as a whole by the integration of all links in the food supply chain; what is more, it can achieve the most important objective by measuring and sorting the risk level of different links. These superiorities, which could be obtained by comparing with other methods, not only could reflect the potential in evaluating the quality and risk level in food supply chain but also could make up the gap between the traditional food risk evaluation from the aspect of single or independent link and the modern food risk evaluation from the aspect of the whole food supply chain and provide a reference for the public and private sectors when making decisions on food quality management.

5. Conclusion

The food industry in China is facing various challenges, including but not limited to reducing food waste, improving food quality and safety, and becoming more ecofriendly. To address these challenges and improve the food quality, it is critical to implement efficient and effective quality and operations management measures by identifying food quality risk factors and evaluating the risk levels of each link in the food supply chain. This study adopted a comprehensive approach to establish a fuzzy evaluation model for food quality risk evaluation. Through an extensive literature review, a quality risk indicator system for the food supply chain covering five evaluation objectives and 55 quality risk evaluation indicators was built to provide a basis for evaluating the food quality risk level. Then, the methods of FCEM and FMECA were applied based on surveys of experts to evaluate the food quality risk level. The results of a computational experiment suggest that this approach is reasonable for evaluating the food quality risk level.

The resulting quality risk evaluation model of the food supply chain can be used as a general guideline to highlight the most important objectives regarding the level of food quality risk evaluation according to the results of the computational experiment. Furthermore, the evaluation model provides a useful foundation for future case analyses. The government agencies responsible for food quality in supply chain management may adopt this model to assess the food quality risk level of each region. A food industry sector might also apply this model to review the strengths and weaknesses of its current food quality risk management so that better quality management plans could be developed for the food supply chain. In addition, compared with other provinces, it is clear that the food quality risk levels of the same objects, such as sales and consumption risk and logistics, warehousing, and transportation risk, are different due to the differences in cold chain logistics technology and eating habits. This finding

Table 5

Indicators	Assessment comments	Level of food quality risk indicators				
		1	2	3	4	5
Raw material supply risk Q_1						
Soil pollution Q_{11}						
Air pollution Q_{12}						
Water pollution Q_{13}						
Heavy metal pollution Q_{14}						
Illegal use of additives Q_{15}						
Residual inputs Q_{16}						
Microbial contamination Q_{17}						
Pathogenic bacteria pollution Q_{18}						
Transgenic technology risk Q_{19}						
Production and processing risk Q_2						
Illegal use of additives Q_{21}						
Contamination with foreign matter Q_{22}						
Inability to wash a food product clean Q_{23}						
Presence of detergent residue Q_{24}						
Pathogen contamination Q_{25}						
Microbial contamination Q_{26}						
Uncertified processing equipment Q_{27}						
Nonstandardized processing personnel operation Q_{28}						
Insufficient processing environment Q_{29}						
Insufficient processing equipment Q_{210}						
Inappropriate packaging Q_{211}						
Insufficient packaging quality Q_{212}						
Uncertified packaging logo Q_{213}						
Insufficient assurance of personnel health Q_{214}						
Quality inspection risk Q_{215}						
Insufficient storage process Q_{216}						
Logistics, warehousing, and transportation risk Q_3						
Inventory control technology Q_{31}						
Intelligent temperature-control facilities Q_{32}						
Transport vehicle sanitation Q_{33}						
Cold chain hardware supporting facilities Q_{34}						
Third-party logistics level Q_{35}						
Partner technology platform convergence Q_{36}						
Product portfolio storage transport Q_{37}						
Cold chain logistics information transmission Q_{38}						
Logistics road infrastructure Q_{39}						
Illegal operation of logistics transport personnel Q_{310}						
Vehicle scheduling and monitoring information feedback Q_{311}						
Sales and consumption risk Q_4						
Selling expired food Q_{41}						
Falsifying the date of production Q_{42}						
False reporting of food ingredients Q_{43}						
Poor sanitation in dining establishments Q_{44}						
Poor sanitation conditions Q_{45}						
Improper disposal of waste food Q_{46}						
Poor sanitation in cooking facilities Q_{47}						
Improper eating methods Q_{48}						
Insufficient storage environment Q_{49}						

Table 5: Continued.

Indicators	Assessment comments	Level of food quality risk indicators				
		1	2	3	4	5
Government regulatory risk Q_5						
Imperfect regulatory system Q_{51}						
Supervisory staff level Q_{52}						
Supervisor moral hazard Q_{53}						
Supervision channels Q_{54}						
Regulatory organization Q_{55}						
Regulatory agency efficiency Q_{56}						
Regulatory process management Q_{57}						
Regulatory results feedback Q_{58}						
Regulatory detection technology Q_{59}						
Other risks Q_{510}						
Imperfect regulatory system Q_{51}						
Supervisory staff level Q_{52}						

shows that the food quality risk level is relative, requiring managers to take the actual situation into account when making decisions on food quality risk management.

There may be two limitations in this study. First, systematic deficiencies of the risk evaluation indicator system may exist because the potential negative interactions among indicators were not taken into account, which might affect the validity of the evaluation results. Second, the effectiveness of this proposed model was verified by a computational experiment. However, the selected case to be implemented was consistent for only the problem of food quality risk evaluation. Thus, the results of the computational experiment may not be generalizable. Future research should address these limitations.

Appendix

A. A Sample of Survey Questionnaire

A.1. Basic Information

(1) Gender:

- □ male
- □ female

(2) Age:

- □ 20–29
- □ 30–39
- □ 40–49
- □ 50 or more

(3) Length of service:

- □ Within 1 year
- □ 1–5 years
- □ 6–10 years
- □ 11–20 years
- □ 20 years or more

(4) Your duties:

(5) Department:

(6) Nature of your department:

- □ Farmer
- □ Food processing enterprise
- □ Logistics warehousing enterprise
- □ Retailer and consumer
- □ Government regulator
- □ other

A.2. Assessment Comments of FSCHP's Food Quality Risk Indicators. See Table 5.

B. A Sample of Expert Scoring Table

See Table 6.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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Table 6

Factors	Scoring																			
	Occurrence probability (H)					Severity after occurrence (S)					Likelihood of detection (D)					Ability to control and compensate (C)				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Raw material supply risk Q_1																				
Soil pollution Q_{11}																				
Air pollution Q_{12}																				
Water pollution Q_{13}																				
Heavy metal pollution Q_{14}																				
Illegal use of additives Q_{15}																				
Residual inputs Q_{16}																				
Microbial contamination Q_{17}																				
Pathogenic bacteria pollution Q_{18}																				
Transgenic technology risk Q_{19}																				
Production and processing risk Q_2																				
Illegal use of additives Q_{21}																				
Contamination with foreign matter Q_{22}																				
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Presence of detergent residue Q_{24}																				
Pathogen contamination Q_{25}																				
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Uncertified processing equipment Q_{27}																				
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Insufficient processing environment Q_{29}																				
Insufficient processing equipment Q_{210}																				
Inappropriate packaging Q_{211}																				
Insufficient packaging quality Q_{212}																				
Uncertified packaging logo Q_{213}																				
Insufficient assurance of personnel health Q_{214}																				
Quality inspection risk Q_{215}																				
Insufficient storage process Q_{216}																				

Table 6: Continued.

Factors	Scoring																			
	Occurrence probability (H)					Severity after occurrence (S)					Likelihood of detection (D)					Ability to control and compensate (C)				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Logistics, warehousing, and transportation risk Q_3																				
Inventory control technology Q_{31}																				
Intelligent temperature-control facilities Q_{32}																				
Transport vehicle sanitation Q_{33}																				
Cold chain hardware supporting facilities Q_{34}																				
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Regulatory results feedback Q_{58}																				
Regulatory detection technology Q_{59}																				
Other risks Q_{510}																				

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References

[1] T. Chen, L. Wang, and J. Wang, "Transparent assessment of the supervision information in china's food safety: a fuzzy-anp comprehensive evaluation method," *Journal of Food Quality*, vol. 2017, Article ID 4340869, 14 pages, 2017.

[2] P. Pinstrupandersen, "Food security: definition and measurement," *Food Security*, vol. 1, no. 1, pp. 5–7, 2009.

[3] Food security: Policy brief, FAO's Agriculture and Development Economics Division, Rome: Author, FAO, 2006.

[4] R. H. Abiyev, K. Uyar, U. Ilhan et al., "Assessment of food security risk level using type 2 fuzzy system," *Procedia Computer Science*, vol. 102, pp. 547–554, 2016.

[5] X. J. Chen, "An analytical framework and supervision system for chinese government to protect food quality and safety," *Journal of Nanjing Normal University*, vol. 1, pp. 29–36, 2011.

[6] L. J. Hubbard and C. Hubbard, "Food security in the United Kingdom: external supply risks," *Food Policy*, vol. 43, pp. 142–147, 2013.

[7] T. Gomiero, "Food quality assessment in organic vs. conventional agricultural produce: findings and issues," *Applied Soil Ecology*, 2017.

[8] L. Ludikhuyze, A. Van Loey, I. S. Denys, and M. Hendrickx, *Effects of High Pressure on Enzymes Related to Food Quality: From Kinetics to Process Engineering*, Kluwer Academic/plenum Publishers, New York, NY, USA, 2002.

[9] Z.-H. Ding, J.-T. Li, and B. Feng, "Radio frequency identification in food supervision," in *Proceedings of the 9th International Conference on Advanced Communication Technology, ICACT '07*, pp. 542–545, IEEE, Okamoto, Kobe, Japan, 2007.

[10] R. Wendyvan and F. Lynnj, "Consumer perceptions of food quality and safety and their relation to traceability," *British Food Journal*, vol. 110, no. 10, pp. 1034–1046, 2008.

[11] A. V. Cardello, "Food quality: relativity, context and consumer expectations," *Food Quality and Preference*, vol. 6, no. 3, pp. 163–170, 1995.

[12] M. K. A. Kadir, E. Hines, K. Qaddoum et al., "Food security risk level assessment: a fuzzy logic-based approach," *Applied Artificial Intelligence*, vol. 27, no. 1, pp. 50–61, 2013.

[13] S. Zhao and X. Yang, "Food safety risk assessment in whole food supply chain based on catastrophe model," *Advance Journal of Food Science and Technology*, vol. 5, no. 12, pp. 1557–1560, 2013.

[14] P. J. A. Chavez and C. Seow, "Managing food quality risk in global supply chain: a risk management framework," *International Journal of Engineering Business Management*, vol. 4, no. 1, 2012.

[15] X. J. Wang, D. Li, and X. L. Shi, "A fuzzy model for aggregative food safety risk assessment in food supply chains," *Production Planning and Control*, vol. 23, no. 5, pp. 377–395, 2012.

[16] J. Wang, T. Chen, and J. Wang, "Research on cooperation strategy of enterprises' quality and safety in food supply chain," *Discrete Dynamics in Nature and Society*, vol. 2015, Article ID 301245, 15 pages, 2015.

[17] F. Jie, K. Barton, and K. Wang, "Food quality as a supply chain performance indicator for Australian cattle producers," in *Proceedings of the 10th International Research Conference on Quality, Innovation and Knowledge (QIK)*, pp. 202–208, Monash University, Melbourne, Australia, 2011.

[18] A. Turi, G. Goncalves, and M. Mocan, "Challenges and competitiveness indicators for the sustainable development of the supply chain in food industry," *Procedia - Social and Behavioral Sciences*, vol. 124, pp. 133–141, 2014.

[19] H. Nilsson, H. J. Trienekens, and S. W. F. Omta, "Total quality indicators for the food production chain: is there a need for more labelling?" 2002.

[20] A. Salvo, G. T. La, V. Mangano et al., "Toxic inorganic pollutants in foods from agricultural producing areas of Southern Italy: level and risk assessment," *Ecotoxicology and Environmental Safety*, vol. 148, pp. 114–124, 2017.

[21] X. Wang, D. Li, and X. Shi, "A fuzzy model for aggregative food safety risk assessment in food supply chains," *Production Planning and Control*, vol. 23, no. 5, pp. 377–395, 2012.

[22] L. A. Zadeh, "Fuzzy sets," *Information and Control*, vol. 8, no. 3, pp. 338–353, 1965.

[23] Q. Xie, J.-Q. Ni, and Z. Su, "Fuzzy comprehensive evaluation of multiple environmental factors for swine building assessment and control," *Journal of Hazardous Materials*, vol. 340, pp. 463–471, 2017.

[24] J. Cheng and J.-P. Tao, "Fuzzy comprehensive evaluation of drought vulnerability based on the analytic hierarchy process—an empirical study from Xiaogan City in Hubei Province," *Agriculture and Agricultural Science Procedia*, vol. 1, pp. 126–135, 2010.

[25] Y. Y. Chen, *Fuzzy Mathematics*, Huazhong University of Science and Technology Press, Wuhan, China, 1984.

[26] R. Zhu, Q. Liang, and H. Zhan, "Analysis of aero-engine performance and selection based on fuzzy comprehensive evaluation," *Procedia Engineering*, vol. 174, pp. 1202–1207, 2017.

[27] A. Yazdani, S. Shariati, and A. Yazdani-Chamzini, "A risk assessment model based on fuzzy logic for electricity distribution system asset management," *Decision Science Letters*, vol. 3, no. 3, pp. 343–352, 2014.

[28] Z. X. He, *Fuzzy Mathematics and Its Application*, Tianjin Science and Technology Publishing House, Tianjin, China, 1983.

[29] W. Li, W. Liang, L. Zhang, and Q. Tang, "Performance assessment system of health, safety and environment based on experts' weights and fuzzy comprehensive evaluation," *Journal of Loss Prevention in the Process Industries*, vol. 35, pp. 95–103, 2015.

[30] J.-F. Chen, H.-N. Hsieh, and Q. H. Do, "Evaluating teaching performance based on fuzzy AHP and comprehensive evaluation approach," *Applied Soft Computing*, vol. 28, pp. 100–108, 2015.

[31] F. Deng, C. Wang, and X. Liang, "Fuzzy comprehensive evaluation model for flight safety evaluation research based on an empowerment combination," in *Proceedings of the 10th International Conference on Management Science and Engineering Management*, pp. 1479–1491, 2017.

[32] A. Afful-Dadzie, E. Afful-Dadzie, S. Nabareseh, and Z. K. Oplatková, "Tracking progress of African Peer Review Mechanism (APRM) using fuzzy comprehensive evaluation method," *Kybernetes*, vol. 43, no. 8, pp. 1193–1208, 2014.

[33] L. KrizOva, A. Vollmannova, E. Margitanova et al., "Can be blueberries the risk food and raw material?" *Journal of Microbiology Biotechnology and Food Sciences*, vol. 1, pp. 769–776, 2012.

[34] M.-H. Moncel, A.-M. Moigne, M. Arzarello, and C. Peretto, "Raw material supply areas and food supply areas: integrated approach of the behaviors," in *Proceedings of the XV World UISPP Congress*, 2007.

[35] A. Olsson and C. Skjoldebrand, "Risk management and quality assurance through the food Ssupply chain - case studies in the Swedish food industry," *The Open Food Science Journal*, vol. 2, no. 1, pp. 49–56, 2008.

[36] W. Huang and L. Chen, "Research on food safety and quality control process modeling and simulation based on the supply chain," *Journal of Convergence Information Technology*, vol. 8, no. 4, pp. 34–42, 2013.

[37] T. Matuszek, "Food production quality and risk assessment on machinery design," *Journal of Hygienic Engineering and Design*, 2012.

[38] H. Omura, K. Tanaka, and N. Sugimoto, "A hygienic hazard list for risk assessment of food processing machinery," *The journal of Reliability Engineering Association of Japan*, vol. 32, pp. 367–375, 2010.

[39] T. Matuszek, "Basic factors for food processing equipment hygienic design and its cleanabilities with minimal contamination risk," *Journal of Hygienic Engineering and Design*, pp. 38–45, 2014.

[40] X. U. Fucai and S. Meng, "Analysis on risk management of the food supply chain," in *Midwives, Research and Childbirth*, pp. 465–475, Springer, New York, NY, USA, 1989.

[41] L. I. U. Yongsheng and W. E. I. Xuan, "Food supply chain risk management situation evaluation model based on factor analysis," *International Business and Management*, vol. 12, no. 2, pp. 40–46, 2016.

[42] A. Marucheck, N. Greis, C. Mena, and L. Cai, "Product safety and security in the global supply chain: issues, challenges and research opportunities," *Journal of Operations Management*, vol. 29, no. 7-8, pp. 707–720, 2011.

[43] I. Vlachos and E. Dimitropoulos, "Supply chain management, 3rd party logistics and food quality and safety: evidence from Greece," in *Proceedings of the nternational Conference on Management in Agrifood Chains and Networks*, 2006.

[44] L. Xu, Q. Dong, and K. Xiao, "Research on early-warning model for food supply chain risk based on logistic regression," in *Proceedings of the 2010 International Conference on Logistics Engineering and Intelligent Transportation Systems, LEITS2010*, pp. 1–4, IEEE, Wuhan, China, 2010.

[45] L. Leger and D. Berkin, "Method for simulating and modeling the presence and growth of microbes, including pathogens and spoilage organisms, through a food supply chain," 2004.

[46] B. H. Susheela and L. M. Cathleen, "Factors affecting microbial load and profile of potential pathogens and food spoilage bacteria from household kitchen tables," *Canadian Journal of Infectious Diseases and Medical Microbiology*, vol. 2016, Article ID 3574149, 6 pages, 2016.

[47] R. M. W. Yeung and J. Morris, "Food safety risk: consumer perception and purchase behaviour," *British Food Journal*, vol. 103, no. 3, pp. 170–187, 2001.

[48] C. Hawkes, "Sales promotions and food consumptionnure," *Nutrition Reviews*, vol. 67, no. 6, pp. 333–342, 2009.

[49] R. Mo, W. Yeung, and Morris J., *Food Safety Risk: Consumer Food Purchase Models*, Cranfield University, Bedfordshire, UK, 2002.

[50] B. Bilska, M. Wrzosek, D. Kołozyn-Krajewska, and K. Krajewski, "Risk of food losses and potential of food recovery for social purposes," *Waste Management*, vol. 52, pp. 269–277, 2016.

[51] H. Wei, University B. W., Study on supermarket food safety risk management based on supply chain, Logistics Technology, 2013.

[52] X. Gellynck, W. Verbeke, J. Viaene et al., "Quality management in the food supply chain: how does the food industry interact with consumers, retailers and public authorities?" in *Proceedings of the Quality assurance, risk management and environmental control in agriculture and food supply networks: Proceedings of the 82nd Seminar of the European Association of Agricultural Economists (EAAE) held in Bonn*, 2003.

[53] V. Hill, "Government regulation of food quality: international and in france and the US," in *A Kaizen Approach to Food Safety*, pp. 53–82, Springer International Publishing, Berlin, Germany, 2014.

[54] B. F. V. Waarden, *Ttraditions, transactions, and trust: the public and private regulation of food*, Ansell, Richmond, Australia, 2005.

[55] D. K. Casey, "Three puzzles of private governance: global gap and the regulation of food safety and quality," *SSRN Electronic Journal*, 2009.

[56] V. Mceachern, A. Bungay, S. B. Ippolito et al., "4–Regulatory verification of safety and quality control systems in the food industry," *Auditing in the Food Industry*, vol. 73, no. 23, pp. 29–51, 2001.

[57] G. Skogstad, "Regulating food safety risks in the European Union:a comparative perspective," in *What's the Beef*, pp. 213–236, 2006.

[58] J. Zhou and S. Jin, "Overview of food safety management in China," in *Food Safety Management in China: A Perspective from Food Quality Control System*, pp. 1–32, 2015.

[59] S.-H. Wang, M.-T. Lee, P.-A. Château, and Y.-C. Chang, "Performance indicator framework for evaluation of sustainable tourism in the Taiwan coastal zone," *Sustainability*, vol. 8, no. 7, article 652, 2016.

[60] C. Deng, J. Liu, Y. Liu, and Z. Yu, "A fuzzy comprehensive evaluation for metropolitan power grid risk assessment," in *Proceedings of the 2016 International Conference on Smart Grid and Clean Energy Technologies, ICSGCE '16*, pp. 1–5, IEEE, Chengdu, China, 2016.

[61] J. An, "Evaluating the electric power utilities' risk based on an improved FCEM under the smart grid environment," in *Proceedings of the 2010 International Conference on Computer, Mechatronics, Control and Electronic Engineering*, pp. 468–471, IEEE, Changchun, China, 2010.

[62] L. Gong and C. Jin, "Fuzzy comprehensive evaluation for carrying capacity of regional water resources," *Water Resources Management*, vol. 23, no. 12, pp. 2505–2513, 2009.

[63] T. J. Dukes, B. M. Schmidt, and Y. Yu, "FMECA-based analyses: A SMART foundation," in *Proceedings of the 2017 Annual Reliability and Maintainability Symposium*, 2017.

[64] A. Certa, F. Hopps, R. Inghilleri, and C. M. La Fata, "A Dempster-Shafer Theory-based approach to the Failure Mode, Effects and Criticality Analysis (FMECA) under epistemic uncertainty: application to the propulsion system of a fishing vessel," *Reliability Engineering & System Safety*, vol. 159, pp. 69–79, 2017.

[65] J. M. Sun, M. l. Zhao, M. X. Zhang, and Y. H. Hu, "Investigation report on construction of quality and safety inspection system of agricultural products in Henan Province," *Journal of Henan Agriculture*, vol. 4, pp. 22-23, 2016.

[66] A. Fearne, S. Hornibrook, and S. Dedman, "The management of perceived risk in the food supply chain: a comparative study of retailer-led beef quality assurance schemes in Germany and Italy," *International Food and Agribusiness Management Review*, vol. 4, no. 1, pp. 19–36, 2009.

[67] S. L. Ting, Y. K. Tse, G. T. S. Ho, S. H. Chung, and G. Pang, "Mining logistics data to assure the quality in a sustainable food supply chain: a case in the red wine industry," *International Journal of Production Economics*, vol. 152, pp. 200–209, 2014.

[68] C. Chen, J. Zhang, and T. Delaurentis, "Quality control in food supply chain management: an analytical model and case study of the adulterated milk incident in China," *International Journal of Production Economics*, vol. 152, pp. 188–199, 2014.

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Research Article

How Does Suppliers' Fairness Affect the Relationship Quality of Agricultural Product Supply Chains?

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Although many studies have suggested that the relationship between different supply chain members significantly affects agricultural product quality, suppliers' perceptions of fairness, which greatly influence their decisions on building the relationship quality, are often overlooked. Particularly, the empirical evidence to investigate the impacts of suppliers' fairness on the relationship quality and the factors that affect the suppliers' fairness is missing, and therefore this knowledge gap needs to be filled by new research. Herein, we conducted a survey of 450 agricultural product suppliers and systemically analyzed the impact of antecedents on fairness perception and the impact of fairness perception on relationship quality. In addition, we developed a structural equation model and found that information sharing and price satisfaction had significantly positive effects on procedural fairness and distributive fairness, respectively. Furthermore, our studies demonstrated that procedural fairness is more important in improving the relationship quality than distributive fairness. However, supplier dependence is another important impact factor, and it greatly decreases the positive effects of suppliers' fairness on relationship quality. In summary, the study results provide several managerial implications and extend our understanding of the importance of suppliers' fairness in the relationship quality, which involves product development with respect to the supplier's performance.

1. Introduction

Normally, retailers dominate in agricultural product supply chains. Although large retailers usually gain much more profits from a supply chain than suppliers, suppliers usually undertake most economic risks of the production and markets [1]. When suppliers realize that they are being treated unfairly, they might add unfavorable substances to accelerate the growth of agricultural products and increase the outputs for gaining more profits. The behaviors of suppliers to maximize their benefits have induced some food safety issues, such as melamine milk powders, glue steaks, and plastic seaweeds, which do not only harm the health of consumers, but also greatly damage the brand image of suppliers, leading to bankruptcy of suppliers and the disruption of the whole supply chain. Behavioral economics experiments have shown that people are not completely rational and have fairness perceptions. They do not only compare their own incomes to the incomes of others but also concern the fairness of the distribution and motivation.

Kumar et al. [2] pointed out that fairness is an important factor in determining the channel relationship quality and cooperation performance. People are always friendly to those who treat them fairly, while they punish those who treat them unfairly [3]. Samaha et al. [4] analyzed 500 manufacturing enterprises and their supply chain members through a linear hierarchy model, which proves that unfairness perceptions have a significantly negative impact on the relationship quality. Qin et al. [5] found that fairness perceptions enable enterprises to be more conducive to the performance of supply chains. Their research shows that fairness perceptions have a positive impact on the cooperation performance between the supplier and the retailer when both sides feel fairness during the cooperation. If either side does not feel fairness, the cooperation will not last long. Thus, a good supply chain operation requires fair relationships [6]. Only a fair market environment can enhance the cooperation between the supplier and the retailer and motivate the supplier to improve the product quality. However, current research on fairness perceptions mainly focuses on psychology, sociology, and other fields and ignores the roles of supplier fairness perceptions in Chinese agricultural supply chains. Therefore, we performed studies to investigate the antecedents of perceived fairness and its impacts on the quality of supply chain relationships.

Our studies focus on the relationship quality in agricultural product supply chains and suppliers' fairness. We assume that suppliers' fairness may affect the relationship quality of agricultural product supply chains, and suppliers will not trust retailers. As a result, the agricultural product supply chain cannot achieve the maximal profits, and retailers may decrease the ordering quantity and even switch to other suppliers. Although current studies often highlight the importance of the retailer's fairness perception in regard to repurchase intentions, we found that the supplier's fairness perception could also significantly impact the relationship quality in agricultural product supply chains.

Previous studies focused on fairness from many different dimensions but overlooked the factors related to the relationship between suppliers' fairness and the relationship quality. For instance, Samaha et al. [4] did not distinguish between three dimensions of fairness; Luo [7] focused solely on procedural justice; and Kumar et al. [2], Yilmaz et al. [8], Brown et al. [9], and Griffith et al. [10] focused on procedural and distributive justice. In contrast, we examined the relationship between supplier fairness and relationship quality. In addition, supplier dependence is another important factor that could affect the trust between suppliers and retailers, and therefore we examine its impact on the trust between the suppliers and the retailers, for the first time.

In light of these research gaps, the central issues addressed in this research focus on investigating the impact of two dimensions of supplier fairness on relationship quality. We use survey data from 450 agricultural product suppliers to explore the effect of antecedents (including information sharing, price satisfaction, and environmental stability) on fairness perceptions and the effect of fairness perceptions on relationship quality. In addition, we investigated moderating effects of suppliers' dependence on fairness perceptions, which consequently affect relationship quality (i.e., trust and commitment). Furthermore, the indirect effect of antecedents on relationship quality of agricultural product supply chains was also studied.

The contributions of our studies are fourfold. First, supplier fairness perceptions were utilized as an independent variable to analyze the impacts of this perception on trust among members of the agricultural product supply chains. Second, we studied the relationship between procedural fairness and the agricultural product supply chains. We found that the two latitudes can reflect fairness perceptions more comprehensively than the fairness of latitude alone. Third, our studies characterized the direct and indirect effects of fairness with survey data, which is important because the antecedents of fairness are not directly portrayed in extant researches. Therefore, a consideration of the output of relational quality is required to understand this phenomenon [11]. In addition, we also considered retailer dependence as a key factor in the supply chain management of agricultural products for the first time and included it in this study. Fourth, unlike previous studies, ours investigated the impact of retailer dependence on trust. Our research will greatly promote the studies of the theories of fairness and food supply chain management because many suppliers depend on their retailers for survival.

The remainder of our study is organized as follows. Section 2 provides a theoretical background analysis and presents the hypotheses as well as a supplier-retailer relationship performance model. Section 3 introduces our detailed questionnaire design and tests the validity and reliability of our studies. Section 4 reports our survey results and verifies the appropriateness of its assumptions. Section 5 provides discussion and management implications with our survey data and provides conclusions and points out possible directions for the future research.

2. Theoretical Background and Hypotheses

2.1. Fairness Theory. The fairness or justice theory is derived from exchange and equilibrium theories in the field of sociology and economics. Adams [12] argued that interperson fairness perceptions were primarily derived from comparing one's ratio of outcomes and inputs with others'. Further studies suggested that fairness perceptions are a critical factor in maintaining a cooperative relationship at interorganizational enterprise levels [2, 13]. In fairness theory, fairness is often divided into four dimensions: distributive fairness, procedural fairness, interpersonal fairness, and informational fairness. Distributive and procedural fairness are based on structural aspects [14]. Interpersonal fairness and informational fairness are based on people's reactions and social interactions [15, 16]. Interpersonal fairness focuses on the degree to which people are treated with dignity, politeness, and concern by employers in inner enterprise [16]. It usually plays an important role in an organization that has specific superior and subordinate relationships. In contrast, informational fairness refers to conveying information, including why procedures are formulated in a certain way and why profits are distributed in a certain fashion [17]. The informational fairness is always prominent in a relatively equal relationship.

Distributive fairness was introduced by Adams [12], who confirmed that people's outcome comparison with others' is the main element considered by people when they judge if they were treated fairly. On the personnel level, the formation of distributive fairness is associated with the difference of individual profits. Extended to circumstances involving supply chains and strategic enterprise alliances, distributive fairness is formed in situations in which both parties in the partnership distribute their common earnings in view of each party's contributions, commitment, and responsibility [18]. Because there is a closed relationship between distributive fairness and incomes, distributive fairness can have a strong impact on profit satisfaction. Especially in agricultural product supply chains, most suppliers are in a disadvantaged position, due to the uncertainty of supply demands. The profit of suppliers is so small that they become more sensitive if they are treated unfairly; and, hence, distributive fairness is important for agricultural product suppliers.

In addition, procedural fairness was proposed by Thibaut and Walker [19], and they suggested that people often focus on the fairness of transaction processes, which are used to determine the distribution outcomes of resources and incomes. There are some common grounds between procedural fairness and distributive fairness. For instance, high incomes increase the levels of both procedural and distributive fairness. However, different from distributive fairness, people will perceive the presence of greater procedural fairness when they believe they can control the procedures in question or when they realize that the policies and practices could protect their interests. Procedural fairness was proved to be more important in supply chain circumstances [20–22]. The existence of procedural fairness not only significantly increases the enterprise's integrated performance but also affects cooperative satisfaction.

There are a number of studies about fairness perceptions, which suggest that fairness perception has a positive effect on relationship quality. However, most studies only focused on retailers but neglected the fairness perception of suppliers, especially in the agricultural product industry. Thus, in line with Zaefarian et al. [23], our studies will focus on fairness perceptions in regard to agricultural suppliers, rather than other industries or retailers.

Distributive and procedural fairness gained popularity in studying the supply chain relationship [2, 8, 9, 13]. However, in an agricultural product supply chain, the relationship between suppliers and retailers is typically a loose interorganization cooperation. Moreover, retailers are usually in a dominant position in agricultural product supply chains, and suppliers focus on profits and the procedure of distribution. Therefore, the distributive fairness and procedural fairness are more important than interpersonal fairness and informational fairness in agricultural product supply chains. Our work focuses on the distributive fairness and procedural fairness.

2.2. Relationship Quality. Relationship quality is defined as consisting of characteristics that can reveal the quality of relational ties between two sides in a transaction [24]. In sale channels, better relationship quality can not only decrease the uncertainty of consumers, but also gain consumers' trust [25, 26]. In addition, the relationship between business partners also involves the standards that are used to assess and cognize the commercial intercourse results in business cooperation [27]. Relationship quality consists of multifarious dimensions. In view of interactive relationships and relational benefits, the dimensions of relationship quality, including commitment, cooperation, trust, communication, participation, and skills, are needed to solve conflicts together [28, 29]. In social psychological and strategy alliances, the dimensions of relationship quality refer to tie strength, endurance, frequency, diversity, flexibility, and fairness [30]. There are also some studies that consider trust and commitment as basic construct dimensions of business relationship quality [31, 32]. Moreover, trust and commitment completely capture the essential aspects of supplier-retailer relationships. They are also preconditions to many other dimensions, such as satisfaction and cooperative relationship values. In light of the importance of these two dimensions, we consider trust and commitment as two prime dimensions in this study to define relationship quality.

In behavior theory, trust is defined as an irrational behavior and could be imperative to cooperative relationships in supply chains [33]. Extending to the interorganization scenario, trust means that enterprises care about their partners altruistically and share their common earnings bountifully [34]. Ruyter et al. [35] argued that trust is a driving power arising from spontaneous reliance on partners. Because of the different definitions of trust, trust is multifaceted. Zucker [36] divided trust into two dimensions, which are based on personal and institutional elements, respectively. In psychology, studies related to trust mostly focus on interpersonal trust. In supply chain relationships, enterprises pay more attention to interorganizational trust, which consists of more reliability and benevolence than interpersonal trust [37]. In this study, we agree with Anderson and Narus's [33] studies in regard to capturing the characteristics of trust for agricultural suppliers. We posit that trust encompasses honesty and benevolence. In comparison with trust, honesty is the belief that partners keep their word and fulfill obligations sincerely. Benevolence means that suppliers are firmly convinced that the retailer is concerned about the suppliers' welfare and will not take unexpected actions that would have a negative impact on suppliers. According to supply chain members' cognition in regard to ability and integrity, trust exerts an impact on relationship value and changes supply chain members' behavior. If the trust level between firms and their partners is high, it becomes impossible to adopt opportunistic behaviors. Meanwhile, with the support of trustworthy partners, the market and technical risks of firms will be minimized.

Commitment is also a basic dimension of relationship quality; and its importance is acknowledged by many researchers (e.g., [32, 38]). To some extent, commitment is a ramification of trust; and some researchers believed that commitment refers to the confidence of partners' trust and honesty [39, 40]. In interorganizational relationships, commitment embodies the willingness to maintain a long-lasting partnership launched by a contract [41]. Higher levels of commitment will cause enterprises to make more economical profits [42]. In cooperative relationships, the existence of commitment means that partners will take on the costs of commitment, searching, and finality into consideration, and their partners will not readily turn to alternatives. Commitment promotes the sharing of information and technology among enterprises; hence, there will be a greater appreciation of information and technology. Figure 1 depicts the theoretical model of supplier-retailer relationship performance which is elaborated upon in detail as shown below.

2.3. Antecedents of Fairness Perception. Various supply chain studies indicate that people's fairness perception will be influenced by a number of different factors. For example, Kumar et al. [2] argued that distributive fairness is connected to outcomes. In regard to supply chain relationships, studies of suppliers and manufacturers argue that the benefits of distribution and risk sharing are principal factors that

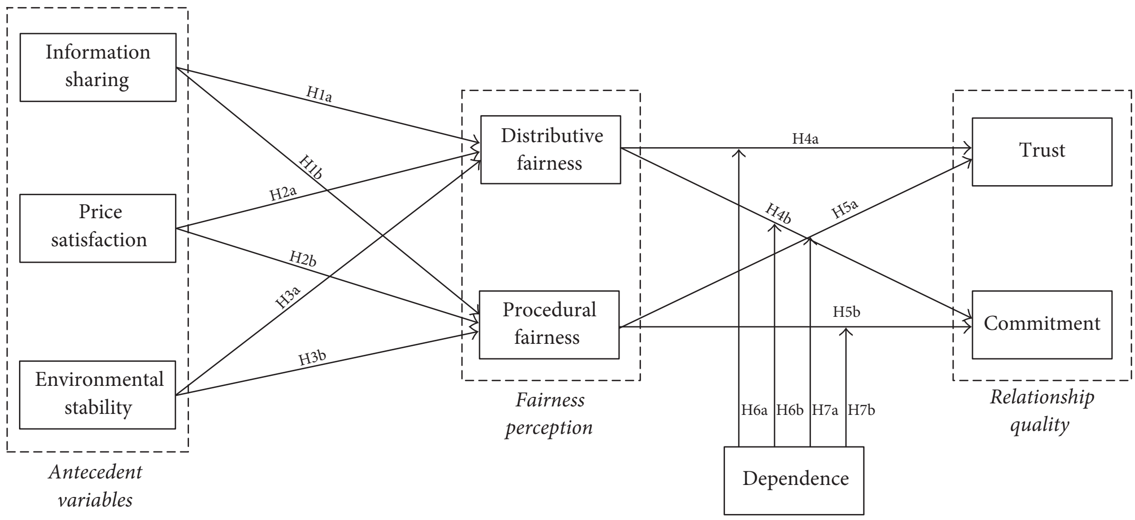

Figure 1: A theory model of supplier-retailer relationship performance.

affect distributive fairness. However, existing studies do not conduct further research on the antecedents of fairness perceptions. In our study, we will explore how information sharing, price satisfaction, and environmental stability affect people's fairness perceptions.

Organizational studies suggest that enterprises information can be broken down into strategy information, transaction information, and operational information [43]. Information sharing improves the management efficiency and operational performance of a supply chain [44]. In supply chain relationships, there are lower levels of information risks and higher levels of overall supply chain performance if enterprises share information [45, 46]. Thus, sharing information is the key factor to allocate resources efficiently, save on transaction costs, and improve the use ratio of information resources. It has been shown that knowing a partner's profit information can make enterprises feel like being treated fairly [5]. Meanwhile, sharing information with a partner about one's own initiative is regarded as a signal of kindness and fairness. However, if an enterprise shares too much confidential information with a partner, this will put the enterprise in a disadvantaged position and hurt the perception of fairness. This characteristic is more obvious in agricultural supply chains. Agricultural product retailers possess a great deal of information about clients, competitors, and enterprise operations, which allows retailers to dominate transaction details such as procurement regulations and prices [47]. Therefore, only rational information sharing can guide agricultural suppliers to make accurate decisions about the output of agricultural products and then reduce unsalable products and meet market requirements. Hence, we believe that effectively using acquired information and rationally sharing information with partners can greatly promote fairness perception, cooperation performance, and supply chain stability. Consequently, we hypothesize the following:

> *H1a, b*: information sharing has a significant positive effect on distributive fairness (a) and procedural fairness (b).

Price is considered to be one of the most important factors that will increase a supplier's fairness perceptions. As far as suppliers are concerned, the impact of price on a long-lasting supply chain is complicated, due to the complexity of the relationship ages, the cooperative nature of relationships, and various market circumstances. Hellberg-Bahr and Spiller [48] suggested that suppliers compare the procurement prices proposed by different retailers before they sell products. This behavior is becoming an important factor in forming price satisfaction and fairness. However, in agricultural supply chains, suppliers lack pricing power because of their inferior position. Therefore, suppliers will pay more attention to retailers' procurement pricing criteria, which involve examining product quality, purchase quantity, geographic position, and relationship age [49]. We argue that the impact of price satisfaction on fairness perception is not only related to whether agricultural suppliers can fairly gain profits or not but also connected to the endurance and stability of the cooperative relationship in question. Therefore, suppliers are sensitive to prices and high levels of price satisfaction will effectively enhance the cooperative stability of the supply chain in question. Thus, we propose the following:

> *H2a, b*: price satisfaction has a positive impact on distributive fairness (a) and procedural fairness (b).

Environmental stability is defined as the ability of an enterprise to forecast the future markets, policies, and other factors accurately, according to the current external environment [50]. The external environment is the prime factor that is considered before enterprises make decisions. When market circumstances are unstable, enterprises usually do not want to be risk averse. They will reduce their dependence on a single partner to maintain their level of flexibility [51]. Kumar et al. [2] demonstrated that an uncertain environment will weaken the positive impact of fairness perception on relationship quality. Many unpredictable factors will emerge in a stagnant market environment. In psychology, growing uncertainty makes enterprises become more suspicious of each other, which is not conducive to constructing favorable cooperative relationships. This phenomenon is more general in the agricultural product market because suppliers are always facing uncertain external environments, such as price fluctuations and changes of climate. Thus, these suppliers are more inclined to be affected by the external environment. Nevertheless, a stable environment can enable suppliers to prepare for future variations in advance. Consequently, they could optimize their relationships with retailers. Thus, we suggest the following:

> *H3a, b*: environmental stability is positively related to distributive fairness (a) and procedural fairness (b).

2.4. Fairness Perception and Relationship Quality. A number of studies have examined the influence of fairness perceptions on relationship quality. Aryee et al. [52] argued that distributive fairness and procedural fairness had remarkable positive effects on relationship quality. Luo [18] proved that procedural fairness and interpersonal fairness were conducive to relationship quality. Ellis et al. [53] showed that procedural fairness was more important than informational fairness. Liu et al. [14] proved that procedural fairness and informational fairness were important in relationship quality, and therefore procedural fairness is more significant.

In the literature on supply chain management, evidence exists to support the argument that fairness perceptions are closely linked to honesty and benevolence in regard to trust [54]. Based on research conducted in the automotive industry, Zaefarian et al. [23] suggested that fairness perceptions led to high levels of trust. Hemmert et al. [55] pointed out that suppliers' trust in the buyer can be promoted by establishing fairness in the supplier-buyer relationship. In agricultural supply chains, the effect of distributive fairness perception and procedural fairness perception on trust may be particularly prominent because the positions of suppliers and retailers are asymmetrical. Highly favorable distributive fairness promotes mutual trust between suppliers and retailers, leading to a willingness to maintain long-term cooperation [10, 52]. In fact, favorable mutual trust eliminates opportunistic behavior caused by ineffective communication and conflicts of interest in interorganizational relationships. Accordingly, this causes the willingness of involved parties to maintain cooperation and plays an important role in improving market vitality. Thus, we propose the following:

> *H4a, b*: both distributive fairness (a) and procedural fairness (b) have positive effects on trust.

Commitment in this context is defined as an ongoing relationship with another and is important enough to warrant a great deal of effort to maintain it [50]. According to Kumar et al. [2], procedural fairness has a relatively strong influence on commitment, compared with distributive fairness. Furthermore, with the deepening of cooperation, suppliers pay more attention to procedural fairness, instead of distributive fairness, and they also expect to acquire respect, not just lucrative returns, from retailers. Suppliers cannot perceive favorable commitment when they lack respect, even if retailers have already successfully maintained high levels of distributive fairness with suppliers [56]. In agricultural product supply chains, the characteristics of commitment are embodied by the contracts. Nonperformance behaviors, such as rejection or postponing deliveries, may pose risks to suppliers. Moreover, agricultural products are usually perishable, and these behaviors may not only result in huge losses to suppliers, but also disturb the stability of the product supplies and prices. Thus, we posit the following:

> *H5a, b*: distributive fairness (a) and procedural fairness (b) have positive effects on commitment.

2.5. The Moderating Effect of Dependence. In supply chain channels, dependence refers to an enterprise's need to maintain a relationship with a partner, in order to fulfill the enterprise's objectives [57]. If the ability of an enterprise to replace a partner is deficient, we posit that the enterprise is dependent upon its partners [58]. Dependence consists of two concepts: total interdependence (the sum of both enterprises' dependence) and asymmetrical interdependence (the difference in the enterprises' dependence) [59, 60]. Dependence can have a strong impact on maintaining a dyadic relationship [61]. In a supply chain, support and coordination between members can ensure effective operation. Upstream suppliers, such as manufacturers, need an adequate supply of raw materials and timely delivery services. Downstream retailers need a stable supply of products and stable market demand. However, when asymmetrical interdependence exists on a large scale, the more powerful supplier is likely to perform opportunistic behaviors to maximize their own profits due to low risks. We propose that, in agricultural supply chains, suppliers depend heavily on retailers. In terms of the numbers, relatively few retailers and a number of suppliers consistently lead to the supply of agricultural products beyond the requirements at hand. Moreover, agricultural suppliers expect to sell products as soon as possible because of the perishable nature of the products. Consequently, intensive sale willingness increases the dependence of suppliers on retailers. Thus, we propose that there exists highly asymmetrical interdependence between suppliers and retailers.

As symmetrical interdependence increases, the occurrence of divergence and conflict decreases. So, symmetrical dependence therefore has a positive effect on relationship quality. Excessive asymmetrical interdependence, on the other hand, increases powerful enterprises' ability to replace partners and, therefore, could damage the trust and commitment between supply chain numbers. Relationship quality decreases a lot due to unfair treatment in an asymmetrical relationship and a lack of incentives to cultivate trust and commitment with partners. Therefore, we believe that the more the suppliers depend on retailers; the less the influence of suppliers' fairness perceptions on relationship quality will be. Furthermore, dependence more likely leads to building cooperative circumstances and affects relationship quality indirectly. Thus, we hypothesize the following:

> *H6a, b*: the positive effect of distributive fairness on trust (a) and commitment (b) is smaller once considering suppliers' dependence on retailers.

H7a, b: the positive effect of procedural fairness on trust (a) and commitment (b) is smaller once considering suppliers' dependence on retailers.

3. Methodology

3.1. Sample and Data Collection. We tested our hypotheses using matched supplier data drawn from the agricultural product industry in Jiangsu province, which is located in East China. Jiangsu is a developed province, especially in regard to agriculture. There are a large number of agricultural product suppliers in Jiangsu. There are also wholesale distributors of agricultural products, as well as foreign supermarkets, such as Carrefour, Walmart, and PARKnSHOP. This presents ideal circumstances in which we can empirically examine supplier-retailer relationships. Generally, suppliers in Jiangsu province are single working class households with relatively limited number of partners. The suppliers usually cooperate with a few fixed retailers. On the other hand, there are multiple households that supply agricultural products to retailers at the same time. Consequently, the differences between suppliers and retailers lead to tense supplier-retailer relationships, which have aroused extensive concerns for the Chinese government. Suppliers are unable to earn satisfactory profit due to being in a weak position in the supply chain. This situation can not only decrease suppliers' fairness but also decrease the quality of agricultural products. Therefore, it is necessary to study fairness issues in this context to alleviate the tense relationships in this situation.

We designed a series of questionnaires for suppliers. The original questionnaires were designed first in English, and then the English version was translated into Chinese and back-translated into English to ensure the accuracy of the translation. The differences between the original and back-translated English versions were checked by professional translators, and we refined some questions. In the data collection process, we conducted face-to-face interviews as well as mailing questionnaires to 1,000 informants in Jiangsu province. The common characteristics among these informants were shown as follows: all of them are working class households and have cooperative relationships with supermarkets or other agricultural product retailers. All questionnaires were anonymous, and we guaranteed confidentiality of data to avoid evaluation apprehension in respondents.

After a month, we received 562 questionnaires. To verify each informant's knowledge of suppliers' cooperative relationships with retailers, as well as their levels of knowledgeability in regard to the survey, we used a seven-point Likert scale (1 = "very low" and 7 = "very high"). We removed 112 informants with scores less than 4 for these questions and ended up with a final supplier sample consisting of 450 participants. The response rate is around 45%, which is adequate for empirical studies. The average operation duration of our supplier samples was approximately five years. A total of 38.9% of suppliers reported annual revenues of less than ¥0.5 million, 32.4% reported annual revenues of ¥0.5–¥1 million, 19.8% reported annual revenues of ¥1-¥2 million, and 8.9% reported annual revenues greater than ¥2 million. After the data collection, we conducted a revisit survey with a sample of 50 nonresponding informants, to assess nonresponse bias. We compared these 50 informants with respondents' data and found that there were no significant differences between responding informants and nonresponding informants. Thus, nonresponse bias did not have an influence on our data.

3.2. Variables and Measurements. We used multi-item models to measure the validity and reliability of our supply chain relationship study. Table 1 outlines the final set of construct scales, Cronbach's alphas, and item loadings. All the items in our construct scales were derived from existing studies, and we made reasonable adjustments to meet our research targets. Antecedents of fairness perception were defined as consisting of three dimensions: information sharing, price satisfaction, and environmental stability. The items for these three dimensions were adapted from Frazier et al. [62], Hellberg-Bahr and Spiller [48], and Heide and John [58] and consisted of six, five, and four items, respectively. Fairness perceptions in our study were conceptualized as two dimensions: distributive fairness and procedural fairness. Distributive fairness is rooted in Price and Mueller [63], with five items, and procedural fairness is rooted in Kim and Mauborgne [64] and Konovsky and Cropanzano [65], with eight items. The construct of relationship quality had several different operational alternatives. In prior literature, relationship quality was usually composed of trust and commitment. Therefore, the measure for trust was adapted from the items posited by Kumar et al. [2], which consist of honesty and benevolence, with five items each. Commitment was adapted from Meyer et al. [66], with three items. Dependence referred to the dependence of suppliers on retailers; it was derived from Frazier et al. [62] and measured through four items.

Due to the constructs of variables being derived from existing literature, we conducted several steps to ensure that the constructs are applicable to our study and to assess the robustness and validity of the constructs. First, we performed an exploratory factor analysis (EFA) on our data. The reliability of the variables was validated by favorable Cronbach's alphas and all of the indexes were greater than 0.72, shown in Table 1. Second, we conducted a confirmatory factor analysis (CFA) using the maximum likelihood method in AMOS 22.0 to evaluate the measurement validity of the constructs [67]. Our CFA results showed a goodness of fit with the data: df = 947, χ^2/df = 1.39, RMSEA = 0.03, GFI = 0.90, CFI = 0.96, TLI = 0.95, and IFI = 0.96. In accordance with the standard of goodness of fit [68, 69], χ^2/df < 0.2, RMSEA < 0.05, GFI, CFI, TLI, and IFI were all equal to or greater than 0.90, thereby confirming a favorable goodness of fit. For convergent validity, all item loadings were greater than 0.64 and significant ($p < 0.01$), and the composite reliability of all the variables ranged from 0.72 to 0.83, showing satisfactory convergent validity (see Tables 1 and 2). We also verified discriminant validity by evaluating average variance extracted (AVE) from each construct; we confirmed that it was greater than the squared correlations between all the construct pairs [70], further demonstrating discriminant validity.

Table 1: Construct overview.

Construct scales	α	Item loadings
Information sharing		
IS1: We can share our business information with the retailer without hesitation.		0.69
IS2: The retailer always notifies us about the relevant information in a timely manner.		0.77
IS3: The retailer informs us about all useful information.	0.79	0.77
IS4: We share product information and business progress with the retailer in a timely manner.		0.86
IS5: We and the retailer believe that the information we share with each other is reliable.		0.80
IS6: We and the retailer cooperate to solve problems together.		0.78
Price satisfaction		
PS1: In general, fresh agricultural product prices are satisfactory.		0.80
PS2: Fresh agricultural product prices correspond with our labor costs.	0.72	0.81
PS3: Most of the fresh agricultural products we sold did not make enough profit (R).		0.63
PS4: In the last decade, we have been satisfied with the purchase prices that the retailer provided.		0.70
PS5: We are satisfied with the current agricultural product prices.		0.66
Environmental stability		
ES1: The fresh agricultural products market has a stable industry volume.		0.82
ES2: The fresh agricultural products market is predictable.	0.72	0.77
ES3: The fresh agricultural products sale forecasts are quite accurate.		0.75
ES4: It is easy to monitor trends in the fresh agricultural product market environment.		0.76
Distributive fairness		
DF1: Our firm's outcomes are fair compared to the efforts and investments that we have made to support the retailer's line.		0.84
DF2: Our firm's outcomes are fair compared to the roles and responsibilities the retailer assigns to our organization.	0.77	0.85
DF3: Our firm's outcomes are fair compared to what other dealers in our industry earn.		0.89
DF4: Our firm's outcomes are fair compared to what the retailer earns from sales through our partnership.		0.88
DF5: Our firm's outcomes are fair compared to the contributions we make to this retailer's marketing efforts.		0.92
Procedural fairness		
PF1: In our relationship with the retailer, a high level of bilateral communication exists.		0.80
PF2: The retailer does not discriminate but rather treats all suppliers similarly.		0.81
PF3: The retailer considers objections seriously, according to the suppliers' policies and programs.		0.78
PF4: The retailer sometimes alters their policies in response to suppliers' objections.	0.83	0.91
PF5: The retailer provides valid reasons for any changes in policies affecting suppliers.		0.80
PF6: The retailer makes an effort to learn the local conditions under which suppliers operate.		0.83
PF7: The retailer is knowledgeable about the local situations faced by suppliers.		0.88
PF8: The retailer treats suppliers with respect and the retailer's behavior is polite and well-mannered.		0.79
Commitment		
COM1: Even if we could, we would not drop the retailer because we like being associated with them.	0.81	0.83
COM2: We want to remain a member of the retailer's network because we genuinely enjoy our relationship with them.		0.76
COM3: Our positive feelings towards the retailer are a major reason why we continue working with them.		0.81
Trust		
HT1: Even when the retailer gives us a rather unlikely explanation, we are confident that they are telling the truth.		0.66
HT2: The retailer has often provided us with information that has later been proven to be inaccurate (R).		0.58
HT3: The retailer usually keeps the promises they make to our firm.		0.71
HT4: Whenever the retailer gives us advice about our business operations, we know they are sharing their best judgments.		0.87
HT5: Our organization can count on the retailer to be sincere.	0.74	0.85
BT1: Though circumstances change, we believe that the retailer is willing to offer us assistance and support.		0.81
BT2: When making important decisions, the retailer is concerned about our welfare.		0.85
BT3: When we share our problems with the retailer, we know that they will respond with understanding.		0.88
BT4: In the future, we can count on the retailer to consider how their decisions and actions will affect us.		0.69
BT5: When it comes to matters that are important to us, we can depend on the retailer's support.		0.82

Table 1: Continued.

Construct scales	α	Item loadings
Dependence		
DE1: The total cost of switching to a competing retailer's line would be prohibitive.		0.64
DE2: The retailer's work with us is very important to our organization.	0.81	0.91
DE3: The quality of the agricultural product the retailer sells is creditable.		0.80
DE4: In our trade area, suppliers would incur the highest costs if we lost our retailer partners.		0.65

Table 2: Means, standard deviations, AVE, CR, correlation matrix, and goodness of fit.

	M	SD	AVE	CR	Correlation matrix (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Information sharing	4.62	1.12	0.61	0.90	1.00							
(2) Price satisfaction	4.76	1.12	0.52	0.74	0.73^{***}	1.00						
(3) Environmental stability	4.67	1.15	0.60	0.71	0.60^{***}	0.53^{***}	1.00					
(4) Distributive fairness	4.78	1.02	0.77	0.94	0.69^{***}	0.79^{***}	0.61^{***}	1.00				
(5) Procedural fairness	4.74	1.06	0.68	0.94	0.87^{***}	0.74^{***}	0.74^{***}	0.71^{***}	1.00			
(6) Trust	4.62	1.17	0.64	0.94	0.80^{***}	0.72^{***}	0.75^{***}	0.71^{***}	0.78^{***}	1.00		
(7) Commitment	4.92	1.11	0.61	0.73	0.73^{***}	0.71^{***}	0.74^{***}	0.76^{***}	0.82^{***}	0.76^{***}	1.00	
(8) Dependence	4.71	1.11	0.59	0.93	0.35^{***}	0.37^{***}	0.50^{***}	0.37^{***}	0.41^{***}	0.46^{***}	0.50^{***}	1.00

Goodness of fit

χ^2/df	df	RMSEA	GFI	CFI	TLI	IFI
1.39	947	0.03	0.90	0.96	0.95	0.96

$^{***}p$ (i.e., significance) < 0.001.

4. Results

After demonstrating the validity and reliability of the data, we introduced three constructs of the antecedents (information sharing, price satisfaction, and environmental stability), two constructs of fairness perception (distributive fairness and procedural fairness), and two constructs of relationship quality (trust and commitment) and dependence (see Figure 1). Because fairness perceptions, trust, and commitment are behavior indexes, they usually contain some measurement variations. Structural equation modeling (SEM), a popular statistical methodology for experimental research [14], allows independent variables and dependent variables to contain measurement variations and deal with multiple dependent variables at the same time. SEM can also deal with the complex affiliation of an index that belongs to multiple factors, and therefore it is a method that is precisely necessary for studying the supplier-retailer relationship in agricultural product supply chains. We conducted SEM with maximum likelihood estimation in AMOS 22.0 to test our hypotheses, which enabled us to test influences with multiple structural paths.

To examine the hypotheses, we proposed (H1, H2, and H3) and analyzed the path from antecedents to fairness perception. The structural equation modeling analysis results show that information sharing has a positive but not a significant effect on distributive fairness (Table 3). In addition, information sharing shows a relatively high positive and significant effect on procedural fairness (β = 0.56, p < 0.001). This result rejected H1a but supported H1b. The path from price satisfaction to fairness perceptions indicates that price satisfaction has positive and significant effects on both distributive fairness (β = 0.57, p < 0.001) and procedural fairness (β = 0.16, p < 0.01). Similarly, environmental stability has a positive and significant influence on distributive fairness (β = 0.23, p < 0.01) and procedural fairness (β = 0.31, p < 0.001). So far, all the hypotheses concerning antecedents to fairness perception were confirmed, except for H1a.

We found that dependence played a mediating role in the relationship between fairness perceptions and relationship quality. We used a control variable method to analyze the effects of dependence. When dependence was absent, distributive fairness had a positive and significant effect on trust (β = 0.29, p < 0.01) and commitment (β = 0.21, p < 0.05). Hypotheses H4a and H4b were thereby supported. Procedural fairness also had a positive and significant effect on trust and commitment, supporting H5a and H5b. However, it is worth noting that the effect of procedural fairness is much stronger than that of distributive fairness (trust: β = 0.61, p < 0.001; commitment: β = 0.66, p < 0.001). Hypotheses H6 and H7 asserted that dependence has a mitigating effect on the link between fairness perception and relationship quality. H6a and H6b were verified by the results, in regard to dependence. The positive effect in the path from distributive fairness × dependence to trust (β = 0.23, p < 0.01) and commitment (β = 0.14) was less than the condition without dependence. By comparing the path from procedural fairness × dependence to trust (β = 0.43, p < 0.001) and commitment (β = 0.52, p < 0.001) with the

Table 3: Results of hypothesis tests.

Antecedents → dependent variable	β
H1a: Information sharing → distributive fairness	0.14
H1b: Information sharing → procedural fairness	0.56^{***}
H2a: Price satisfaction → distributive fairness	0.57^{***}
H2b: Price satisfaction → procedural fairness	0.16^{**}
H3a: Environmental stability → distributive stability	0.23^{**}
H3b: Environmental stability → procedural fairness	0.31^{***}
H4a: Distributive fairness → trust	0.29^{**}
H4b; Distributive fairness → commitment	0.21^{*}
H5a: Procedural fairness → trust	0.61^{***}
H5b: Procedural fairness → commitment	0.66^{***}
H6a: Distributive fairness × dependence → trust	0.23^{**}
H6b: Distributive fairness × dependence → commitment	0.14
H7a: Procedural fairness × dependence → trust	0.43^{***}
H7b: Procedural fairness × dependence → commitment	0.52^{***}

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

path from procedural fairness to trust and commitment, hypotheses H7a and H7b were also confirmed. In summary, except for H1a, all the hypotheses we proposed are approved. Moreover, we computed the indirect effect of each antecedent dimension on relationship quality with fairness perceptions as a mediating variable. Following Bollen's [71] approach, the indirect effects of the mutual antecedents of information sharing, price satisfaction, and environmental stability on trust are 0.38, 0.26, and 0.26, respectively, and the effects on commitment are 0.40, 0.23, and 0.25, respectively. In general, information sharing imposes the strongest effects on relationship quality via fairness perceptions.

5. Discussion and Implications

The objective of this study is to explore the effects of antecedents (information sharing, price satisfaction, and environmental stability) on fairness perceptions (distributive fairness and procedural fairness) perceived by the agricultural product suppliers. In addition, this study examines the effects of fairness perceptions on relationship quality (i.e., trust and commitment) and also undertakes research regarding the moderating effects of dependence in regard to the impact path from fairness perceptions to relationship quality.

Through a structural equation modeling analysis of 450 agricultural product suppliers in China, we found that the antecedents have a positive effect on suppliers' fairness perceptions. In addition to this, the results revealed the sensitivity of different aspects of fairness perceptions to various antecedents.

These results enrich our existing understanding of fairness theory [61]. Many previous studies only focus on the ways in which fairness perceptions affect relationship quality or supply chain partnerships, while the effects of antecedents, such as information sharing, price satisfaction, and environmental stability, on fairness perception are also important. Particularly, the antecedents profoundly influence supply chain relationship quality via fairness perceptions as well. Our results report that, within our sample collected from the agricultural product industry in China, the antecedents of fairness perceptions could enhance suppliers' fairness perceptions. Specifically, information sharing and environmental stability have strong positive effects on procedural fairness. Distributive fairness was found to be more sensitive to price satisfaction. These findings suggest that, in highly asymmetrical relationships, such as between a powerful retailer or distributor and a vulnerable agricultural product supplier, the antecedents of fairness perceptions will determine fairness perceptions with pertinence. Therefore, some specific interpretations were necessary for us to explain our results.

In addition, we found that information sharing has a strong effect ($\beta = 0.56$, $p < 0.001$) on procedural fairness. This finding is consistent with existing information regarding the agricultural industry in China. Chinese suppliers rarely have the opportunities to reach consumers and most of their production actions are based on the family unit. The farmers scale is so small that they lack advanced management concepts and enough technical supports to predict future demands and production situations accurately. Therefore, agricultural product suppliers, composed of working class households, seldom make explicit output plans or deliberately select the varieties of agricultural products to produce in the future. This condition was also one of the prime reasons leading to falls in sales stock-out of products. In contrast to suppliers, retailers can easily obtain consumption information regarding consumers; and consequently, they have more accurate ideas about consumer demands. For instance, some supermarkets, such as Carrefour and Walmart, have conducted consumer consumption data analyses to make reasonable plans for commodity procurement. However, suppliers lack effective approaches to gaining valuable consumers feedback, and they have to place their hopes in retailers or distributors to acquire market information. If retailers share consumers' feedback and market information with suppliers, the information received from retailers will help suppliers make production plans and thereby avoid unnecessary losses caused by excessive production. Thus, suppliers are eager for an equal market. When retailers attach importance to information sharing, the suppliers will perceive fairness as being present.

Our results also suggest that price satisfaction has a more positive effect on distributive fairness ($\beta = 0.57$, $p < 0.001$) than procedural fairness ($\beta = 0.16$, $p < 0.01$). The reasonable interpretation for the significant positive effect of procedural fairness is that suppliers have to sell their products as quickly as possible due to the perishability of agricultural products, which eventually weakens their initiative in the price setting process. The procurement prices offered by retailers are the key factor for distributing the common incomes of the agricultural supply chains and are also connected to suppliers' profits. In other words, procurement prices determine the fairness of income distribution. Thus, suppliers perceive high levels of distributive fairness if they sell their products at satisfying prices.

In order to scrutinize the effect of market environment on fairness perceptions, we conducted several investigations on environmental stability, which involved demand scales and marketing situations. Our results provided full support for our propositions regarding the positive effects of environmental stability on the fairness perceptions. These results indicate that if future market demand scales and sale volumes are predicted accurately, the level of distributive fairness ($\beta = 0.23$, $p < 0.01$) and procedural fairness ($\beta = 0.31$, $p < 0.001$) will increase. This finding is different from those in regard to other industries, such as climate and geographical location, because agricultural outputs possess characteristics of uncertainty. It is necessary for suppliers to maintain environmental stability. We also found that environmental stability has a strong effect on procedural fairness, because long production cycles make it difficult for suppliers to accurately predict the market situation of agricultural products. Therefore, they need outside supports, such as production technology, equipment, and market information, to regulate production. The supports will help suppliers avoid losses from low yields or overproduction, thereby increasing the suppliers' sense of procedural fairness in the supply chain mechanism. Therefore, we conclude that, compared to distributive fairness, environmental stability plays a crucial role in the suppliers' perceptions of procedural fairness.

In addition to this, the results of the investigation revealed that procedural fairness has a strong positive effect on trust ($\beta = 0.61$, $p < 0.001$) and commitment ($\beta = 0.66$, $p < 0.001$). It is worth noting that this result is opposite to prior studies, which report that procedural fairness has no significant impact on trust and commitment, based on research about the automobile manufacturing industry [23]. This result demonstrates that, in agricultural product supply chains, procedural fairness is the prime factor for improving relationship quality. Because vulnerable suppliers are sensitive to procedural fairness, retailers need to proactively formulate a fair cooperation procedure in order to maintain a high level of relationship quality with suppliers. We used two interaction paths (distributive fairness × dependence and procedural fairness × dependence) to perform a moderation test and explored the impact of dependence on the positive effect of fairness perceptions on relationship quality. Under the condition of considering the relational dependence perspectives of suppliers, the positive effect of fairness perceptions on relationship quality is decreased. Dependence is the main element in an asymmetrical environment, and therefore dependence has a negative influence on relationship quality [72]. In an asymmetrical environment, such as in agricultural supply chains, suppliers lack long-lasting selling lines because the number of suppliers is far greater than that of retailers. As a consequence of these issues, suppliers have to rely on retailers or distributors in many ways to ensure their profits. If suppliers' dependence increases, greater losses will be incurred if retailers breach cooperation contracts. This perspective also damages the relationship quality between supply chain members. Hence, an effective way to improve relationship quality is one of the most important policies for governmental regulators to formulate for suppliers, which would contribute to creating an equal supply chain mechanism and, in turn, improve the partnership between suppliers and retailers.

We also scrutinized the indirect effects of antecedents on relationship quality. We found that indirect positive effects of information sharing, price satisfaction, and environmental stability on trust are 0.38, 0.26, and 0.26, respectively, and the indirect positive effects of these antecedents on commitment are 0.40, 0.23, and 0.25, respectively. We found that the positive effects of antecedents on fairness perceptions could enhance supply chain relationship quality. The result also suggested that information sharing had the strongest indirect positive effect on trust and commitment, because information sharing of the retailer with suppliers will increase the trust of suppliers in retailers. It would have been concluded that information sharing plays a key role for supply chains to increase their relationship quality from an indirect pattern.

5.1. Theoretical Implications. Several theoretical implications can be deduced from our study. First, we add antecedents to organizational fairness research in supply chain management. Prior studies have traditionally focused on the effect of fairness perceptions on relationship quality or supply chain performance and have failed to take into account the impact of the antecedents of fairness perceptions on relationship quality. This study fills this gap by conducting antecedents of fairness perception model in interorganizational circumstances and exploring the ways in which the antecedents change fairness perceptions and relationship quality of agricultural product supply chains. We found that information sharing, price satisfaction, and environmental stability had significant positive effects on suppliers' fairness perceptions. By comparing the strength of the indirect effects of different dimensions of antecedents on fairness perceptions, some factors including information sharing and price satisfaction had a greater effect on procedural fairness and distributive fairness, respectively, than others. Our results also revealed that antecedents had positive indirect effects on trust and commitment, and the effects of information sharing are the strongest. Thus, our findings indicate that suppliers were majorly concerned about the predictability of future market trends and market information provided by retailers, from the perspective of procedural fairness. Furthermore, rational and considerable procurement prices inspire the distributive fairness of suppliers. These two dimensions of fairness perceptions reduce the conflict and uncertainty in the supply chain operating process, leading to improving the supply chain members' satisfaction and maintaining efficient functioning in the long run.

To further investigate fairness perceptions in partnerships, we assessed the effect of fairness perceptions on relationship quality of agricultural product supply chains. The results demonstrated that suppliers' procedural fairness perceptions had stronger impacts on trust and commitment than suppliers' distributive fairness. This result is largely in line with Kumar et al. [2]. In order to draw on the results regarding the way in which information sharing and environmental stability have a more significant impact on procedural fairness than distributive fairness, we verified the mediating function of the fairness perceptions in the path of antecedents to relationship quality, revealing that highly favorable information sharing exerts the strongest positive effect on trust and commitment. Therefore, we support the argument that antecedents play an important role in indirectly improving relationship quality.

Moreover, we introduced dependence into the link between fairness perception and relationship quality to test its moderating influence with the help of an interaction approach. The results of our analysis demonstrate that suppliers' dependence mitigates the effect of distributive fairness and procedural fairness on both dimensions of relationship quality. This finding suggests that relationship quality is less sensitive to fair treatment from retailers when the dependence of suppliers is taken into consideration. In fact, when a supplier is highly dependent on a dominating retailer, the relationship quality will not improve effectively, even if retailers treat them fairly. Hence, under such circumstances, suppliers may adopt two alternative strategies: the first strategy is that they terminate their cooperation with retailers to avoid the benefit losses caused by high levels of dependence, and the other strategy is that they maintain their cooperation with retailers in view of the cost increase, due to the transfer of partners. However, problems regarding profit conflict and unfair treatment also exist in the latter option and so this situation is not helpful in maintaining the safety of food quality. In order to ensure high levels of cooperation quality within a supply chain, third-party regulators should formulate relevant policies to reduce the dependence of suppliers on retailers, thereby balancing both parties' positions in the supply chain.

5.2. Managerial Implications. Our findings have practical implications for both managers of supply chain members and governmental regulators. Above all, improving the management quality of agricultural products requires managers to understand what is harmful to the quality of agricultural products and the interactional relationship between internal systematic factors. Researchers have recognized that long-term stable relationships within supply chains have positive effects on the performance of the supply chains and the quality of the products [73]. Therefore, improving supply chain members' relationship quality is crucial in promoting the quality of products.

First, both supply chain members and governmental regulators should understand that information sharing is the main driver of procedural fairness, trust, and commitment. Our study reveals that information sharing has the strongest direct effect on procedural fairness and the strongest indirect effect on trust and commitment. In reality, agricultural production in China still operates largely within a small economy and lacks aspects of large-scale operations. There are a number of information blind spots in agricultural product supply chains. As a result of this, there exists serious information asymmetry between suppliers and retailers. Indeed, in our reviews, some interviewees claimed that they usually choose agricultural products to plant depending on the prices of the last year. This kind of behavior easily incurs an imbalance between supplies and demands. Our finding verifies the important impact of information sharing on relationship quality and provides clear evidence to prove that high levels of information fairness are necessary for a healthy relationship. Thus, governmental regulators should provide some ways of sharing market information, such as building an Internet platform which allows retailers to update the demand situation of products, or suppliers issuing information about inventories and products for sale.

Second, retailers should pay more attention to suppliers' fairness and preserve suppliers' fairness in all aspects. Although antecedents (such as information sharing) are important in increasing relationship quality, they are not direct drivers. Rather, our results show that relationship quality has a closer connection to distributive fairness and process fairness. Retailers should set reasonable prices to ensure the fair allocation of supply chain profits and the legitimate earning of suppliers in order to ensure that suppliers' distributive fairness can be established. One important finding of our study is that procedural fairness has a stronger effect on relationship quality than distributive fairness. Hence, the recommendation for retailers is that they should preferentially focus on the fairness during transaction processes, such as responding to the requests of suppliers in a timely manner and being proactive in communicating with suppliers. Furthermore, during our interviews, we investigated the effects of retailers' attitudes on suppliers' fairness perceptions and found that bad manners could also damage procedural fairness. Our survey results reveal that 38% of suppliers decided to terminate their cooperation with current retailers due to the offensive behaviors of that retailer, such as a rude or discourteous attitude. Therefore, retailers should realize that vulnerable suppliers are unlikely to tolerate impolite behaviors. To consolidate the fairness perceptions of suppliers, retailers should train their employees to communicate and interact with suppliers in an appropriate manner. Although the four dimensions of fairness are all important in the supply chain, the agricultural product supply chain we focused on is a loose supply chain. The cooperation between the supplier and the retailer is a loose interorganization cooperation. Therefore, distributive fairness and process fairness play a much more important role in relationship than informational fairness and interpersonal fairness. There also exists a close supply chain in which the cooperation relationship between the supplier and the retailer is a close cooperation. For example, the supply chain of Yonghui supermarket and its supplier of proprietaries is a close supply chain. Informational fairness and interpersonal fairness probably play a much more important role in relationship quality in such supply chain.

Third, governmental regulators should support and help small suppliers through various ways. The results of our study demonstrate that dependence mitigates the positive effects of fairness perceptions on relationship quality. Indeed, suppliers are more likely to suffer unfair treatment, such as a breach of contracts or the forcing down of procurement prices, if they are extremely dependent on retailers. For instance, one of our interviewees mentioned how his distributors had violated their contract: "The distributor issued an order request about purchasing all the products after harvest, but during the production they had not provided any supports or informed us the specification of the goods. Finally, after we had grown the products, they said our products were unqualified and refused to purchase any of them." Thus, governmental regulators need to supervise the transaction behavior in agricultural product supply chains. For example, regulators could enforce various measures or establish credibility and benefit sharing incentive mechanisms to closely link the benefits of the two parties, thereby avoiding situations in which retailers harm the interests of suppliers. Moreover, dispersing small-scale farming is the main reason why suppliers assume an inferior position in the supply chain. Hence, integrating multisuppliers and expanding the scale of production appropriately would help suppliers protect their lawful rights and realize the objectives of food quality management [74].

5.3. Limitations and Future Research. Despite the great theoretical and managerial contributions of this study, there are still few limitations. First, a primary finding of this study concerns the moderating effects of dependence on the path from fairness perceptions to relationship quality. However, there is the possibility that antecedents to fairness perceptions also have impacts on dependence. Therefore, future research may consider dependence as a dependent variable and analyze the interactions between dependence and the antecedents to fairness perceptions. The second limitation is that we only focus on the supplier side of the supply chain relationship. Retailers' perceptions are also essential for promoting the relationship quality of supply chains. Therefore, further studies are needed to examine the relationships between every construct from retailers' perspectives. Third, our data were collected from a single country (China). Although it is helpful to eliminate transnational variations as latent noises in the model, this may lead to our conclusions suffering from a lack of universality. Future studies could collect data from multiple countries to testify how different geographical environments influence the supplier-retailer relationship in supply chains.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] U. Broll, P. Welzel, and K. P. Wong, "Price risk and risk management in agriculture," *Contemporary Economics*, vol. 7, no. 2, pp. 17–20, 2013.

[2] N. Kumar, L. K. Scheer, and J. E. Steenkamp, "The effects of supplier fairness on vulnerable resellers," *Journal of Marketing Research*, vol. 32, no. 1, pp. 54–65, 1995.

[3] M. Rabin, "Incorporating fairness into game theory and economics," *American Economic Review*, vol. 83, no. 5, pp. 1281–1302, 1993.

[4] S. A. Samaha, R. W. Palmatier, and R. P. Dant, "Poisoning relationships: Perceived unfairness in channels of distribution," *Journal of Marketing*, vol. 75, no. 3, pp. 99–117, 2011.

[5] F. Qin, F. Mai, M. J. Fry, and A. S. Raturi, "Supply-chain performance anomalies: Fairness concerns under private cost information," *European Journal of Operational Research*, vol. 252, no. 1, pp. 170–182, 2016.

[6] X. Zhao, B. Huo, W. Selen, and J. H. Y. Yeung, "The impact of internal integration and relationship commitment on external integration," *Journal of Operations Management*, vol. 29, no. 1-2, pp. 17–32, 2011.

[7] Y. Luo, "How important are shared perceptions of procedural justice in cooperative alliances?" *Academy of Management Journal (AMJ)*, vol. 48, no. 4, pp. 695–709, 2005.

[8] C. Yilmaz, B. Sezen, and E. Tumer Kabadayi, "Supplier fairness as a mediating factor in the supplier performance-reseller satisfaction relationship," *Journal of Business Research*, vol. 57, no. 8, pp. 854–863, 2004.

[9] J. R. Brown, A. T. Cobb, and R. F. Lusch, "The roles played by interorganizational contracts and justice in marketing channel relationships," *Journal of Business Research*, vol. 59, no. 2, pp. 166–175, 2006.

[10] D. A. Griffith, M. G. Harvey, and R. F. Lusch, "Social exchange in supply chain relationships: The resulting benefits of procedural and distributive justice," *Journal of Operations Management*, vol. 24, no. 2, pp. 85–98, 2006.

[11] J. M. George and G. R. Jones, "The role of time in theory and theory building," *Journal of Management*, vol. 26, no. 4, pp. 657–684, 2000.

[12] J. S. Adams, "Inequity in social exchange," in *Advances in Experimental Social Psychology*, pp. 267–299, Academic Press, New York, NY, USA, 1965.

[13] S. Suh, "Fairness and relationship quality perceived by local suppliers: In search of critical success factors for international retailers," *Journal of Global Marketing*, vol. 18, no. 1-2, pp. 5–19, 2004.

[14] Y. Liu, Y. Huang, Y. Luo, and Y. Zhao, "How does justice matter in achieving buyer-supplier relationship performance?" *Journal of Operations Management*, vol. 30, no. 5, pp. 355–367, 2012.

[15] R. J. Bies and J. S. Moag, "Interactional justice: Communication criteria of fairness," in *Research on negotiation in organizations*, R. J. Lewicki, B. H. Sheppard, and M. H. Bazerman, Eds., vol. 1, pp. 43–55, JAI Press, Greenwich, CT, USA, 1986.

[16] J. Greenberg, "Employee theft as a reaction to underpayment inequity: the hidden cost of pay cuts," *Journal of Applied Psychology*, vol. 75, no. 5, pp. 561–568, 1990.

[17] J. Greenbreg, "The social side of fairness: interpersonal and informational classes of organizational justice," in *Justice in the workplace: Approaching fairness in human resource management*, R. Cropanzano, Ed., Erlbaum, Hilladale, NJ, USA, 1993.

[18] Y. Luo, "The independent and interactive roles of procedural, distributive, and interactional justice in strategic alliances," *Academy of Management Journal (AMJ)*, vol. 50, no. 3, pp. 644–664, 2007.

[19] J. Thibaut and L. Walker, *Procedural justice: A psychological analysis*, Lawrence Erlbaum Associates, Hillsdale, NJ, USA, 1975.

[20] J. A. Colquitt, M. J. Wesson, C. O. L. H. Porter, D. E. Conlon, and K. Y. Ng, "Justice at the millennium: A meta-analytic review of 25 years of organizational justice research," *Journal of Applied Psychology*, vol. 86, no. 3, pp. 425–445, 2001.

[21] Y. Luo, "Procedural fairness and interfirm cooperation in strategic alliances," *Strategic Management Journal*, vol. 29, no. 1, pp. 27–46, 2008.

[22] D. P. S. Chia, C. M. Lau, and S. L. C. Tan, "The relationships between performance measures and employee outcomes: The mediating roles of procedural fairness and trust," *Studies in Managerial and Financial Accounting*, vol. 28, pp. 203–232, 2014.

[23] G. Zaefarian, Z. Najafi-Tavani, S. C. Henneberg, and P. Naudé, "Do supplier perceptions of buyer fairness lead to supplier sales growth?" *Industrial Marketing Management*, vol. 53, pp. 160–171, 2015.

[24] J. K. Huntley, "Conceptualization and measurement of relationship quality: Linking relationship quality to actual sales and recommendation intention," *Industrial Marketing Management*, vol. 35, no. 6, pp. 703–714, 2006.

[25] L. A. Crosby, K. R. Evans, and D. Cowles, "Relationship quality in services selling: an interpersonal influence perspective," *Journal of Marketing*, vol. 54, no. 3, pp. 68–81, 1990.

[26] W. Lu and J. Wang, "The influence of conflict management styles on relationship quality: The moderating effect of the level of task conflict," *International Journal of Project Management*, vol. 35, no. 8, pp. 1483–1494, 2017.

[27] M. Holmlund, "The D and D model - Dimensions and domains of relationship quality perceptions," *The Service Industries Journal*, vol. 21, no. 3, pp. 13–36, 2001.

[28] J. Mohr and R. Spekman, "Characteristics of partnership success: Partnership attributes, communication behavior, and conflict resolution techniques," *Strategic Management Journal*, vol. 15, no. 2, pp. 135–152, 1994.

[29] K. Storbacka, T. Strandvik, and C. Gronroos, "Managing Customer Relationships for Profit: The Dynamics of Relationship Quality," *International Journal of Service Industry Management*, vol. 5, no. 5, pp. 21–38, 1994.

[30] J. A. Young, *Strategic Alliances: Are They Relational by Definition*, Indiana State University, Indiana, Ind, USA, 2000.

[31] V. Kashyap and E. Sivadas, "An exploratory examination of shared values in channel relationships," *Journal of Business Research*, vol. 65, no. 5, pp. 586–593, 2012.

[32] A. G. Abdul-Muhmin, "Instrumental and interpersonal determinants of relationship satisfaction and commitment in industrial markets," *Journal of Business Research*, vol. 58, no. 5, pp. 619–628, 2005.

[33] J. C. Anderson and J. A. Narus, "A model of distributor firm and manufacturer firm working partnerships," *Journal of Marketing*, vol. 54, no. 1, pp. 42–58, 1990.

[34] I. Geyskens, J.-B. E. M. Steenkamp, and N. Kumar, "Generalizations about trust in marketing channel relationships using meta-analysis," *International Journal of Research in Marketing*, vol. 15, no. 3, pp. 223–248, 1998.

[35] K. D. Ruyter, L. Moorman, and J. Lemmink, "Antecedents of Commitment and Trust in Customer-Supplier Relationships in High Technology Markets," *Industrial Marketing Management*, vol. 30, no. 3, pp. 271–286, 2001.

[36] L. G. Zucker, "Production of trust: Institutional sources of economic structure," in *Research in Organizational Behavior*, vol. 8, pp. 53–111, 1986.

[37] S. Ganesan, "Determinants of Long-Term Orientation in Buyer-Seller Relationships," *Journal of Marketing*, vol. 58, no. 2, p. 1, 1994.

[38] S. Ganesan, S. R. Brown, B. J. Mariadoss, and H. Ho, "Buffering and amplifying effects of relationship commitment in business-tobusiness relationships," *Journal of Marketing Research*, vol. 47, no. 2, pp. 361–373, 2010.

[39] J. L. Skeem, J. E. Louden, D. Polaschek, and J. Camp, "Assessing relationship quality in mandated community treatment: blending care with control," *Psychological Assessment*, vol. 19, no. 4, pp. 397–410, 2007.

[40] A. Gustafsson, M. D. Johnson, and I. Roos, "The effects of customer satisfaction, relationship commitment dimensions, and triggers on customer retention," *Journal of Marketing*, vol. 69, no. 4, pp. 210–218, 2005.

[41] E. Anderson and B. Weitz, "Determinants of Continuity in Conventional Industrial Channel Dyads," *Marketing Science*, vol. 8, no. 4, pp. 310–323, 1989.

[42] S. B. Modi and V. A. Mabert, "Supplier development: Improving supplier performance through knowledge transfer," *Journal of Operations Management*, vol. 25, no. 1, pp. 42–64, 2007.

[43] J. Li, R. Sikora, M. J. Shaw, and G. Woo Tan, "A strategic analysis of inter organizational information sharing," *Decision Support Systems*, vol. 42, no. 1, pp. 251–266, 2006.

[44] F. Ye and X. J. Xu, "Impact of trust and relationship commitment among supply chain partners on information sharing and operational performance," *Systems Engineering: Theory Practice*, vol. 29, no. 8, pp. 36–48, 2009.

[45] R. B. Handfield and C. Bechtel, "The role of trust and relationship structure in improving supply chain responsiveness," *Industrial Marketing Management*, vol. 31, no. 4, pp. 367–382, 2002.

[46] P. Y. Tong and J. L. Crosno, "Are information asymmetry and sharing good, bad, or context dependent? A meta-analytic review," *Industrial Marketing Management*, vol. 56, pp. 167–180, 2016.

[47] G. L. Frazier, "Organizing and managing channels of distribution," *Journal of the Academy of Marketing Science*, vol. 27, no. 2, pp. 226–240, 1999.

[48] A. Hellberg-Bahr and A. Spiller, "How to treat farmers fairly? Results of a farmer survey?" *International Food and Agribusiness Management Review*, vol. 15, no. 3, pp. 87–98, 2012.

[49] T. C. Schroeder, C. E. Ward, J. R. Mintert, and D. S. Peel, "Value-Based Pricing of Fed Cattle: Challenges and Research Agenda," *Review of Agricultural Economics*, vol. 20, no. 1, p. 125, 1998.

[50] R. M. Morgan and S. D. Hunt, "The Commitment-Trust Theory of Relationship Marketing," *Journal of Marketing*, vol. 58, no. 3, p. 20, 1994.

[51] J. B. Heide, "Interorganizational Governance in Marketing Channels," *Journal of Marketing*, vol. 58, no. 1, p. 71, 1994.

[52] S. Aryee, P. S. Budhwar, and Z. X. Chen, "Trust as a mediator of the relationship between organizational justice and work outcomes: Test of a social exchange model," *Journal of Organizational Behavior*, vol. 23, no. 3, pp. 267–285, 2002.

[53] K. M. Ellis, T. H. Reus, and B. T. Lamont, "The effects of procedural and informational justice in the integration of related acquisitions," *Strategic Management Journal*, vol. 30, no. 2, pp. 137–161, 2009.

[54] J. A. Colquitt and J. B. Rodell, "Justice, trust, and trustworthiness: A longitudinal analysis integrating three theoretical perspectives," *Academy of Management Journal (AMJ)*, vol. 54, no. 6, pp. 1183–1206, 2011.

[55] M. Hemmert, D. Kim, J. Kim, and B. Cho, "Building the supplier's trust: Role of institutional forces and buyer firm practices," *International Journal of Production Economics*, vol. 180, pp. 25–37, 2016.

[56] T. R. Tyler and E. A. Lind, "A Relational Model of Authority in Groups," *Advances in Experimental Social Psychology*, vol. 25, no. C, pp. 115–191, 1992.

[57] M. Zhang and B. Huo, "The impact of dependence and trust on supply chain integration," *International Journal of Physical Distribution and Logistics Management*, vol. 43, no. 7, pp. 544–563, 2013.

[58] J. B. Heide and G. John, "The role of dependence balancing in safeguarding transaction-specific assets in conventional channels," *Journal of Marketing*, vol. 52, no. 1, p. 20, 1988.

[59] I. Geyskens, J.-B. E. M. Steenkamp, L. K. Scheer, and N. Kumar, "The effects of trust and interdependence on relationship commitment: A trans-Atlantic study," *International Journal of Research in Marketing*, vol. 13, no. 4, pp. 303–317, 1996.

[60] B. Lauranne, "Vertical trade relationships: The role of dependence and symmetry in attaining organizational goals," *Journal of Marketing Research*, vol. 29, no. 1, pp. 65–75, 1992.

[61] D. A. Griffith, J. J. Hoppner, H. S. Lee, and T. Schoenherr, “The Influence of the Structure of Interdependence on the Response to Inequity in Buyer-Supplier Relationships,” *Journal of Marketing Research*, vol. 54, no. 1, pp. 124–137, 2017.

[62] G. L. Frazier, E. Maltz, K. D. Antia, and A. Rindfleisch, “Distributor sharing of strategie information with suppliers,” *Journal of Marketing*, vol. 73, no. 4, pp. 31–43, 2009.

[63] J. L. Price and C. W. Mueller, *Handbook of Organizational Measurements*, Pittman, Marshfield, Mass, USA, 1986.

[64] W. C. Kim and R. A. Mauborgne, “Implementing global strategies: The role of procedural justice,” *Strategic Management Journal*, vol. 12, no. 1 S, pp. 125–143, 1991.

[65] M. A. Konovsky and R. Cropanzano, “Perceived Fairness of Employee Drug Testing as a Predictor of Employee Attitudes and Job Performance,” *Journal of Applied Psychology*, vol. 76, no. 5, pp. 698–707, 1991.

[66] J. P. Meyer, N. J. Allen, and C. A. Smith, “Commitment to organizations and occupations: extension and test of a three-component conceptualization,” *Journal of Applied Psychology*, vol. 78, no. 4, pp. 538–551, 1993.

[67] J. F. Hair, W. C. Black, B. J. Babin, R. E. Anderson, and R. L. Tatham, *Multivariate Data Analysis: A Global Perspective*, Prentice Hall, Upper Saddle River, NJ, USA, 2010.

[68] F. Chan, G. K. Lee, E.-J. Lee, C. Kubota, and C. A. Allen, “Structural equation modeling in rehabilitation counseling research,” *Rehabilitation Counseling Bulletin*, vol. 51, no. 1, pp. 44–57, 2007.

[69] B. G. Tabachnick and L. S. Fidell, *Using Multivariate Statistics*, Allyn and Bacon, Boston, MA, USA, 2007.

[70] C. Fornell and D. F. Larcker, “Evaluating structural equation models with unobservable variables and measurement error,” *Journal of Marketing Research*, vol. 18, no. 1, pp. 39–50, 1981.

[71] K. A. Bollen, *Structural Equations with Latent Variables*, John Wiley & Sons, New Jersey, NJ, USA, 1989.

[72] N. Kumar, L. K. Scheer, and J. E. Steenkamp, “The Effects of Perceived Interdependence on Dealer Attitudes,” *Journal of Marketing Research*, vol. 32, no. 3, p. 348, 1995.

[73] B. Fynes, S. de Búrca, and D. Marshall, “Environmental uncertainty, supply chain relationship quality and performance,” *Journal of Purchasing and Supply Management*, vol. 10, no. 4-5, pp. 179–190, 2004.

[74] C. Ménard and P. G. Klein, “Organizational issues in the agrifood sector: Toward a comparative approach,” *American Journal of Agricultural Economics*, vol. 86, no. 3, pp. 750–755, 2004.

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Research Article

Bundle Pricing Decisions for Fresh Products with Quality Deterioration

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How to sell fresh products quickly to decrease the storage cost and to meet customer quality requirement is of vital importance in the food supply chain. Bundling fresh products is an efficient strategy to promote sales and reduce storage pressure of retailers. In this paper, we consider the bundle pricing decisions for homogeneous fresh products with quality deterioration. The value of fresh products with quality deterioration is approximated as an exponential function based on which customer's reservation prices are calculated. A nonlinear mixed integer programming model is used to formulate the bundle pricing problem for fresh products. By adding auxiliary decision variables, this model is converted into a mixed integer linear program. Numerical experiments and sensitive analysis are conducted to provide managerial insights for bundling fresh products with quality deterioration.

1. Introduction

A fresh product is an item that continues to deteriorate over time and causes its quality and value to diminish, such as fruits, vegetables, seafood, and meat. The market for fresh products has been expanding for years and became an important part of economic development. For example, in China, the scale of fresh product retailers has been increasing with the rate of 15% every year and has reached to 1,300 billion in 2016, which accounts for 52% of the total agriculture output [1]. However, the biochemical and physiological changes lead to the qualitative and quantitative deterioration of the fresh products, which accounts for a great amount of losses to consumers and retailers. Statistic results show that the quantity loss rate of fresh fruits and vegetables reaches up to 20% in China [2]. The cost of unsold products before their sell-by-date is estimated to be billions of dollars each year [3]. Consequently, how to sell fresh products quickly to decrease the storage cost and meet customer quality requirement is of vital importance in the fresh product supply chain and is a current managerial concern as well as an important research issue.

Bundling fresh products is an efficient way to promote selling of fresh products. It means selling two or more fresh products together in one united price [4]. From the practical perspective, bundling strategy provides an efficient method to achieve business objectives and has been proven in many industries, for example, grocery retailers [5], television providers [6], and holiday packages [7]. From the theoretical perspective, bundling strategy gives a novel viewpoint to consider how to improve the social surplus in the area of fresh product operations management. Firstly, bundling could attract more consumers by a lower-price. For example, when the peach is sold at a price of 2 dollars per pound, the bundle will be sold at 3 dollars with two pounds together. Secondly, bundling can reduce the storage by accelerating the selling speed of fresh products. Finally, bundling can enrich the quality control theory through bundling promotion for those fresh products with potential of spoilage.

However, the decision for bundling fresh products is not easy. The main reason is because the change of the qualitative and quantitative deterioration in fresh products will lead to the decrease on the value perceived by consumers [8]. The food quality has always played an important role in the retail process since it has been considered as a direct factor to influence a consumer's purchase decision [9]. Since everyone prefers a fresher product, the price has to be in accordance with the freshness of the products. Otherwise, the bundle will lose its attractive power to the consumer. Consequently, it is difficult to decide a bundle with the right amount, at a very appropriate price and on the right time, to maximize the retailers profit when the quality demands of the consumers are satisfied. Only when the profit of bundling is higher than that of unbundling does the strategy have managerial meanings.

In this paper, we consider the bundle pricing decisions for fresh products with quality deterioration. We consider the bundle of homogeneous fresh products. The value of fresh products with quality deterioration is approximated as an exponential function based on which the customer's reservation prices are calculated. A nonlinear mixed integer programming model is used to formulate the bundle pricing problem for fresh products. By adding auxiliary decision variables, this model is converted into a mixed integer linear program and solved by CPLEX. Numerical experiments and sensitive analysis are conducted to provide managerial insights for bundling fresh products with quality deterioration.

2. Literature Review

Our research is most related to two streams of literature, namely, research on the bundle pricing problem and on the problem of pricing for products with deterioration. In this section, we will review the related academic work from the following two areas.

(1) Bundle Pricing Problem. The composition and pricing of bundles have been widely studied. Bundle sells can eliminate the heterogeneity of customers and extract customer surplus in order to achieve economic and marketing goals [4]. There are two streams of bundle pricing literature. The first stream is from the strategic level to bundle a typical kind of products, for example, information product [10] and food product [11]. Managerial insights are provided from the strategic level. The second stream is from the operational level with focus on how to give an optimal scheme of pricing and composition of bundles. The mostly used methods are probability model [12], Bayes model [13], and MILPs (Mixed integer linear programs) [14]. MILPs are efficient when the number of products is large [15]. A mixed integer linear programing model was proposed by Hanson and Martin (1990) [14] to address the bundle and pricing problems for the first time. Then some academic work extended the model to adapt to new problems. For example, Jiang et al. (2011) [5] proposed a multistage online bundle method, and Mayer et al. (2013) [7] considered the bundle problem with capacity constraints. Wu et al. [16] studied the customized bundle under which consumers decide on the composition of the bundle while the seller determines the size and price of the bundle. And the cardinality of the set of solutions increases linearly with the number of single products [7]. However, when the marginal costs of products are high and different from each other, the customized bundle cannot be implemented.

(2) Pricing for Products with Deterioration. Recently, significant researches combine pricing for perishable products with quality deterioration. We review this part from the demand representation, decisions on pricing and deterioration inventory, and dynamic pricing methods. Firstly, one of the issues in pricing perishable product is to measure the time-and-price sensitive demand, and reference price effect is the mostly used method. For example, Hardie et al. (1993) demonstrated that differences between observed and reference quality can significantly affect purchase probabilities [17] through empirical study. Dye and Yang (2016) modeled the deteriorating goods pricing strategy with reference price effects [18]. Secondly, a great number of models have been proposed to investigate the deterioration inventory. For example, Qin et al. (2014) consider the pricing and lot-sizing problem when the quantity of fresh products is deteriorating simultaneously [3]. Bai and Kendall (2008) assume that the demand rate is dependent on the displayed inventory and the freshness of an item, but the deterioration of freshness is not connected with the deterioration characteristics of fresh produce [19]. Finally, dynamic pricing is the mostly used method for perishable produce for its flexible response to the real-time demand. For example, Wang and Li (2012) presented a dynamic pricing model with accurate quality indicator to maximize food retailer's profit and reduce food spoilage waste [20]. Liu et al. (2015) formulate a joint dynamic pricing and preservation model for perishable foods from selling a given initial inventory of food [9].

The existing findings provide some fundamental elements for our research. Due to the characters of the bundle pricing problem with quality deterioration, the following work has to be studied in this research. Firstly, how to approximate the value of bundles consisting multiple fresh products with quality deterioration. Secondly, when multiple products and time periods are considered, how to formulate the problem is worth further study. Our research aims to bridge the gaps in current literature by approximating the time related value of fresh product bundles, and by providing a mixed integer nonlinear programming model to bundle homogeneous fresh products with quality deterioration. These findings can provide operational tools for the grocery retailer to make pricing strategy and carry out the inventory and promotion activities on agriproducts.

3. Problem Description and Formulation

3.1. Problem Descriptions. In this section, we formulate the optimal bundling and pricing problem for a fresh product with quality deterioration. We consider one kind of fresh product. The model is formulated from the seller's (he) perspective who provides one kind of fresh product to consumers (she) within the life cycle. For example, a fruit retailer provides peaches to consumers. Due to the quality deterioration of peaches, the retailer decides to bundle multiple units of peaches from the second day at a lower unit price as shown in Figure 1. The retailer is faced with the

	1st day	\$8 for 1 unit of peaches
	2nd day	\$14 for 2 units of peaches
	3rd day	\$10 for 3 units of peaches

FIGURE 1: An example of bundling fresh products.

problem to decide how many units of goods to be included in a bundle at a specific time, and how to price these bundles to maximize its profit while consumers maximize their surplus. The basic assumption and notations are as follows.

(1) Number of Potential Consumers I, Bundle J, and Life Cycle Time T. We assume the number of potential consumers is I with index of i. It could be estimated by the historical data in reality. The number of potential bundles is J, with index of j to represent for the number of items included in a bundle. The life cycle time of the fresh product is defined as T with index of t, which begins from 1. At the beginning of each time period, the retailer needs to decide a preferred bundle pricing strategy. For example, as shown in Figure 1, the retailer can bundle two units of peaches on the 2nd day at the price of \$6.

(2) Value of Single Fresh Products with Quality Deterioration. The biochemical and physiological changes lead to the qualitative and quantitative deterioration in fresh products, such as fruits, vegetables, and meat. Quality degradation reduces consumer acceptability as well as the value perceived by the consumers. In order to make the bundle pricing strategy efficiently, it is necessary to develop mathematical models to capture the effect of quality deterioration to the value of consumers. Intuitively, the value of the fresh products is decreased with the decaying of freshness and even drops to zero as time passes by, as shown in Figure 2. The most common method to approximate the perceived value of fresh products is to use the function of product lifecycle. The most studied model is the exponential function to capture the character of quality deterioration. According to Wang and Li (2012) [20], the value function is formulated as

$$V(t) = e^{-b(t-1)}, \tag{1}$$

where b represents the decreasing factor of the fresh product and $b > 0$. A higher level of b demonstrates a quicker deterioration rate.

(3) Reservation Prices of Bundle of Multiple Fresh Products with Quality Deterioration. Following Stigler (1963), we first assume that customer demand information is captured by a

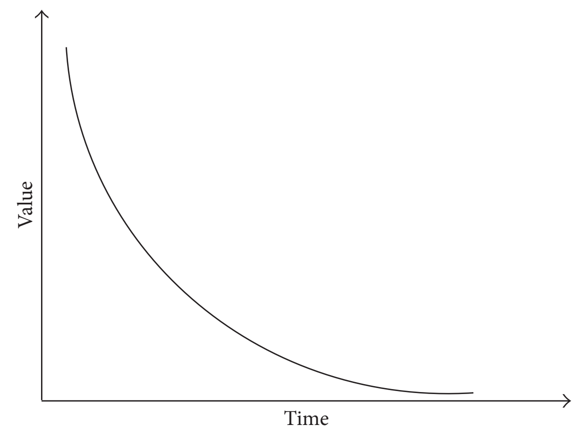

FIGURE 2: The value of fresh products in the life cycle.

vector of reservation prices of the items that go into a bundle [1]. Reservation prices have been widely used in the literature to develop customized pricing models [21]. It is regarded as the consumer's upper bound of willingness to pay for one product. The reservation prices can be fixed or generated by some sort of valuation distribution. For a bundle with multiple fresh products, the reservation prices are decreasing with the quality deterioration and also follow the law of diminishing marginal utility. Let R_{i11} be the reservation price of consumer i for one unit fresh product at the first time period, which is the freshest time. R_{ijt} is the reservation price of consumer i to a bundle consisting j unit fresh products at time t, and it could be formulated by (2), where β is the marginal decreasing rate of multiple products.

$$\begin{aligned} R_{ijt} &= \left[jR_{i11} - \beta\left(j-1\right)^2\right] V(t) \\ &= \left[jR_{i11} - \beta\left(j-1\right)^2\right] e^{-b(t-1)}. \end{aligned} \tag{2}$$

(4) Customer Decisions Rules. Customers' purchasing decisions are determined by their consumer surplus, which means the difference between the total reservation price for a product (bundle) and the price they pay [5]. Customers would prefer a product (bundle) under two conditions: (1)

individual rationality constraint, which means a product may only be bought if its surplus to consumer is greater than 0; (2) compatibility constraint, which indicates a consumer will select a product if it has the highest surplus. The retailer has to consider consumers' optimal decision rules, which appear as constraints in the retailer's optimization problem [16].

A complete list of parameters and variables is shown as follows.

Definitions of the Parameters and Variables Used in the Model

- I: Number of consumers
- i: Indices of consumers
- J: Maximum number of products, J, within a bundle
- j: Indices of bundles with j units of fresh products in it
- T: Total life cycle period of fresh products
- t: Indices of life cycle period of fresh product, which is set from 1
- c_j: Cost of creating a bundle of j goods. This may include the sum of marginal production cost, transaction cost, packaging cost, and so on
- R_{ijt}: Reservation price of consumer i to bundle j at time t. It is decreasing with time and number of items in the bundle. Particularly, R_{i11} represents the reservation price of consumer i for one unit fresh product at the 1st time period
- β: Marginal decreasing rate of multiple products
- b: The deterioration rate of the fresh product.

Decision Variables or Intermediate Variables

- P_{jt}: Price of a bundle with j products to be sold at time t
- Y_{jt}: The decision variable which equals 1 if the retailer chooses to offer the bundle of j goods on the menu, and 0 otherwise
- X_{ijt}: The decision variables which equal 1 if consumer i chooses to buy the bundle of j units of goods at time t
- S_i: Consumer i's surplus for the bundle she chooses.

3.2. Model Formulation. In this section, we formulate the optimal bundling and pricing problem for homogeneous fresh products. The seller providers J units of fresh goods to I consumers within the life cycle of fresh products T. The model is developed from the seller's perspective to optimize the profit while customers maximize their surplus. The problem for the seller is deciding how many goods to be included in each bundle at a specific time and how to price these bundles to maximize his profit, subject to a set of consumers' individual rationality and compatibility constraints. According to the basic notations defined in Section 3.1, we formulate the bundle pricing problem for fresh products as a nonlinear mixed integer programming model. The primal problem is given by IP.

Primal Problem IP

$$\max \quad \sum_{i=1}^{i}\sum_{j=1}^{j}\sum_{T=1}^{T}\left(P_{jt}-c_j\right)X_{ijt}, \tag{3}$$

$$\text{s.t.} \quad S_i=\sum_{j=1}^{J}\sum_{t=1}^{T}\left(R_{ijt}-P_{jt}\right)X_{ijt}, \quad i=1,\ldots,I, \tag{4}$$

$$S_i \geq \left(R_{ijt}-P_{jt}\right)Y_{jt}, \quad i=1,\ldots,I;\ j=1,\ldots,J;\ t=1,\ldots,T, \tag{5}$$

$$\left(R_{ijt}-P_{jt}\right)X_{ijt} \geq 0, \quad i=1,\ldots,I;\ j=1,\ldots,J;\ t=1,\ldots,T, \tag{6}$$

$$R_{ijt}=\left[jR_{i11}-\beta\left(j-1\right)^2\right]\cdot e^{-b(t-1)}, \tag{7}$$

$$\sum_{j=1}^{J}\sum_{t=1}^{T}X_{ijt} \leq 1, \quad i=1,\ldots,I, \tag{8}$$

$$\sum_{j=1}^{J}Y_{jt} \leq 1, \quad t=1,2,\ldots,T, \tag{9}$$

$$X_{ijt} \leq Y_{jt}, \quad i=1,\ldots,I;\ j=1,\ldots,J;\ t=1,\ldots,T, \tag{10}$$

$$S_i \geq 0, \quad i=1,\ldots,I, \tag{11}$$

$$P_{jt} \geq 0, \quad j=1,\ldots,J;\ t=1,\ldots,T, \tag{12}$$

$$X_{ijt}=0 \text{ or } 1, \quad i=1,\ldots,I;\ j=1,\ldots,J;\ t=1,\ldots,T, \tag{13}$$

$$Y_{jt}=0 \text{ or } 1, \quad j=1,\ldots,J;\ t=1,\ldots,T. \tag{14}$$

The objective function (3) maximizes the total profits of the retailer. This is calculated by summing the profit obtained from each customer minus the cost of the bundle. Constraints (4) and (5) define consumer surplus of a bundle and also ensure that each customer maximizes her surplus S_i when making her choice. This is the compatibility constraint which guarantees the final consumer surplus obtained from her choice of bundle is no less than the consumer surplus from any other bundle. Constraint (6) represents the individual rational constraint and ensures that the consumer will choose a bundle only if her surplus on this bundle is nonnegative. Constraint (7) calculates the reservation prices of consumer i for bundle j at time t. Constraint (8) ensures that each customer will purchase no more than one bundle. Constraint (9) ensures that the retailer will provide only one bundle at each time period. Constraint (10) ensures that only if the retailer offers the bundle can customers buy it. Constraints (11) and (12) are nonnegativity constraints for consumer surplus and bundle price. Constraint (13) enforces the integer property of the decision variables with respect to consumer purchases, and constraint (14) enforces the integer property of the decision variables with respect to bundle offerings.

3.3. Model Conversion. Due to the complication of the mixed integer nonlinear programming model, we can hardly solve it. In this paper we convert the model into a mixed integer linear programming model by adding auxiliary decision variables and by using the big M method. The big M method, as one of regular and effective ways to handle the nonlinear integer optimization, has been adopted widely to linearize the nonlinear mixed integer decision variables and convert the original optimization into a linear one [22].

Let $K_{ijt} = P_{jt}X_{ijt}$, $L_{jt} = P_{jt}Y_{jt}$, and by using the big M method, the original model (IP) is converted into a new model (CP). The objective function of IP is converted into function (3.1) in CP, and the constraints (3.2)–(3.4) are restrictions to guarantee the value of K_{ijt} to be equal to $P_{jt}X_{ijt}$. The constraint (4) in IP is converted into (4.1) in CP. The constraint (5) in IP is converted into (5.1), and constraints (5.2)–(5.4) can ensure $L_{jt} = P_{jt}Y_{jt}$. Formulation (15) determines the value of big number M according to the character of the model. Constraints (16) and (17) are nonnegative constraints of new variables K_{ijt} and L_{jt}.

After conversion, the model can be solved by CPLEX. The detailed code of CPLEX is omitted, and we will test the model through numerical experiments in the following section.

Problem CP

$$\max \quad \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\left(K_{ijt} - c_j X_{ijt}\right), \tag{3.1}$$

$$\text{s.t.} \quad K_{ijt} - M\left(1 - X_{ijt}\right) \le p_{jt}, \quad i = 1, \dots, I;\ j = 1, \dots, J;\ t = 1, \dots, T, \tag{3.2}$$

$$K_{ijt} + M\left(1 - X_{ijt}\right) \ge p_{jt}, \quad i = 1, \dots, I;\ j = 1, \dots, J;\ t = 1, \dots, T, \tag{3.3}$$

$$K_{ijt} - MX_{ijt} \le 0, \quad i = 1, \dots, I;\ j = 1, \dots, J;\ t = 1, \dots, T, \tag{3.4}$$

$$S_i = \sum_{j=1}^{J}\sum_{t=1}^{T}\left(R_{ijt}X_{ijt} - K_{ijt}\right), \quad i = 1, \dots, I, \tag{4.1}$$

$$S_i \ge R_{ijt}Y_{jt} - L_{jt}, \quad i = 1, \dots, I;\ j = 1, \dots, J;\ t = 1, \dots, T, \tag{5.1}$$

$$L_{jt} - M\left(1 - Y_{jt}\right) \le P_{jt}, \quad j = 1, \dots, J;\ t = 1, \dots, T, \tag{5.2}$$

$$L_{jt} + M\left(1 - Y_{jt}\right) \ge P_{jt}, \quad j = 1, \dots, J;\ t = 1, \dots, T, \tag{5.3}$$

$$L_{jt} - MY_{jt} \le 0, \quad j = 1, \dots, J;\ t = 1, \dots, T, \tag{5.4}$$

$$R_{ijt}X_{ijt} - K_{ijt} \ge 0, \quad i = 1, \dots, I;\ j = 1, \dots, J;\ t = 1, \dots, T, \tag{6}$$

$$R_{ijt} = \left[jR_{i11} - \beta\left(j - 1\right)^2\right] \cdot e^{-b(t-1)}, \quad i = 1, \dots, I;\ j = 1, \dots, J;\ t = 1, \dots, T, \tag{7}$$

$$\sum_{j=1}^{J}\sum_{t=1}^{T} X_{ijt} \le 1, \quad i = 1, \dots, I, \tag{8}$$

$$\sum_{j=1}^{J} Y_{jt} \le 1, \quad t = 1, 2, \dots, T, \tag{9}$$

$$X_{ijt} \le Y_{jt}, \quad i = 1, \dots, I;\ j = 1, \dots, J;\ t = 1, \dots, T, \tag{10}$$

$$S_i \ge 0, \quad i = 1, \dots, I, \tag{11}$$

$$P_{jt} \ge 0, \quad j = 1, \dots, J;\ t = 1, \dots, T, \tag{12}$$

$$X_{ijt} = 0 \text{ or } 1, \quad i = 1, \dots, I;\ j = 1, \dots, J;\ t = 1, \dots, T, \tag{13}$$

$$Y_{jt} = 0 \text{ or } 1, \quad j = 1, \dots, J;\ t = 1, \dots, T, \tag{14}$$

$$M = 10\sum_{j=1}^{J} c_j, \tag{15}$$

$$K_{ijk} \ge 0, \quad i = 1, \dots, I;\ j = 1, \dots, J;\ t = 1, \dots, T, \tag{16}$$

$$L_{jt} \ge 0, \quad j = 1, \dots, J;\ t = 1, \dots, T. \tag{17}$$

4. Numerical Experiments and Sensitivity Analysis

In this section we study the effectiveness of the proposed model through a couple of numerical experiments.

4.1. The Data Sets

(1) Reservation Prices. Reservation prices have been widely used in literature to develop customized pricing models [13]. In this study, the customers' reservation prices for one unit of fresh product at beginning of the selling season R_{i11} should be set firstly. Following Wu et al. (2008) [16], we assume R_{i11} is normally distributed, $R_{i11} \sim U(r_l^0, r_u^0)$. Here, r_l^0 and r_u^0 are the lower and upper bounds of customers' reservation prices. According to Jiang et al. (2011) [5], the relationship between price, cost, and the highest reservation price is $r_u^0 = 2p - c$, where p and c are posted price and cost of the product. Then the upper bound of reservation price can be derived. As for the lower bound of the reservation price, let $r_l^0 = (1 - \lambda)r_u^0$,

Table 1: Base values of parameters.

I	J	T	c_j ($)	R_{i11} ($)	β	b
10	10	6	$4j$	$U(6,12)$	0.5	0.04

Table 2: An Example of bundle pricing decisions with quality deterioration.

t	Bundle strategy					Unbundle strategy		
	BS (#unit)	BP ($/bundle)	BP/BS ($/unit)	Retailer profit ($)	Consumer surplus ($)	Price ($/unit)	Retailer profit ($)	Consumer surplus ($)
1	8	60.9	7.61	156.58	34.06	9.28	36.97	11.44
2	6	47.8	7.97			8.92		
3	2	16.7	8.35			8.57		
4	1	8.2	8.20			7.63		
5	7	46.97	6.71			6.94		
6	9	51.9	5.77			6.02		

$\lambda \in [0,1]$. Here λ represents the differences between the lowest and highest reservation prices. A higher level of λ means a higher level of heterogeneity in consumers' valuation of the product. Taking the bundle case given in Figure 1 as an example, the price of each unit of peach on the 1st day is $8, and the cost is $4. We found $r_u^0 = 2p - c = 12$ and let $\lambda = 0.5$; then $r_l^0 = 6$, $R_{i11} \sim U(6,12)$.

(2) Setting of Parameters. Let the maximum number of bundle $J = 10$, and the number of customers $I = 10$ in the base experiment. The life cycle time of the fresh products T is set to be 6, which also means the retailer has 6 decision points to launch bundling strategies to promote sales. The cost of each unit of fresh product is set to be $4. Table 1 gives the setting of parameters in the basic example.

4.2. Numerical Results. We use the basic values shown in Table 1 to give an overview of the proposed model for bundling fresh products with quality deterioration. Three indexes are used to show the characteristics of bundles, namely, bundle size (BS, number of items within a bundle), bundle price (BP), and unit product price of a bundle (BP/BS). We also list the results of unbundle strategy, which means in each period the fresh products are sold individually. The results are shown in Table 2 and characteristics of bundle and unbundle strategies in different time periods are compared. Managerial implications are as follows. (1) It is clear that, by using bundle strategy, the retailer profit and consumer surplus are both increased. It is because a bundle with proper price can stimulate consumers to purchase more products. (2) At the beginning of the life cycle, it is better to set a larger-size bundle with a relative lower unit price than the individual price under unbundle strategy ("larger-size & lower-price"). It can be explained that consumers prefer fresh products and an effective bundle at the beginning of product life cycle could bring a higher consumer surplus and consequently increase retailer profit. (3) At the end of life cycle, because the deterioration degree is increased, both the bundle size and bundle price have to be set at a lowest level strategy ("larger-size & lowest-price").

4.3. Sensitivity Analysis. In this section, we investigate how parameters variations affect the bundling strategies. We first study the impacts of changes in the deterioration rate of fresh products. Then changes in the range of customer reservation price distribution are examined subsequently.

(1) Deterioration Rate Variation. The parameter b represents the decreasing factor of the fresh product and $b > 0$. A higher level of b demonstrates a faster deterioration rate. We now set b as 0.01, 0.04, and 0.07. The results are listed in Table 3. It indicates that (1) regardless of the change in b the retailer can still choose to use "larger-size & lower-price" and "larger-size & lowest-price" strategies at the beginning and the end of the life cycle, respectively. (2) As the deterioration rate increases, both the bundle size and unit product price at the end of life cycle are shrunk. It is because that the consumers' value of the product with quality deterioration will drop down shapely. A larger-size bundle at the end of life cycle can hardly derive consumer surplus. Consequently, a relatively smaller size bundle will be preferred if the quality decays faster.

(2) Range Variation of Reservation Prices. The range λ represents the differences between the lowest and highest reservation prices. A higher level of λ means a higher level of heterogeneity in consumer valuation on the product, as well as a lower level of customer consumption level [16]. The effect of changing in λ on the bundle pricing problem is shown in Table 4. It shows that (1) the "larger-size & lower-price" and "larger-size & lowest-price" strategies are still useful at the beginning and the end of the life cycle, respectively. (2) However, under the scenario of lower level λ, the bundle size is relatively smaller, but the unit product price is a little bit higher. The reason lies in the fact that a lower level λ represents a higher consumption level and consumers are almost homogeneous. Consequently, the prices can be set at a high level. But a smaller bundle size is more preferred.

(3) Marginal Decreasing Rate Variation for Multiple Products. Intuitively, for a bundle with multiple homogeneous fresh products, its value to the consumer will follow the rule of

Table 3: Effect of deterioration rate variation on bundle pricing decisions.

t	$b = 0.01$			$b = 0.04$			$b = 0.07$		
	BS (#unit)	BP ($/bundle)	BP/BS ($/unit)	BS (#unit)	BP ($/bundle)	BP/BS ($/unit)	BS (#unit)	BP ($/bundle)	BP/BS ($/unit)
1	8	60.6	7.58	8	60.9	7.61	8	59.6	7.45
2	6	49.2	8.20	6	47.8	7.97	2	16.8	8.42
3	2	17.7	8.85	2	16.7	8.35	5	37.4	7.48
4	6	48.1	8.02	1	8.2	8.20	6	39.8	6.64
5	10	65.1	6.51	7	46.97	6.71	1	7.0	7.01
6	9	61.3	6.81	9	51.9	5.77	3	20.5	6.83

Table 4: Effect of range variation of reservation prices on bundle pricing decisions.

t	$\lambda = 0.2$			$\lambda = 0.5$			$\lambda = 0.8$		
	BS (#unit)	BP ($/bundle)	BP/BS ($/unit)	BS (#unit)	BP ($/bundle)	BP/BS ($/unit)	BS (#unit)	BP ($/bundle)	BP/BS ($/unit)
1	8	60.9	7.61	8	60.9	7.61	9	65.5	7.28
2	4	35.0	8.74	6	47.8	7.97	4	33.9	8.48
3	4	33.6	8.40	2	16.7	8.35	4	32.6	8.15
4	1	9.1	9.07	1	8.2	8.20	9	57.4	6.38
5	3	23.34	7.78	7	46.97	6.71	10	57.5	5.75
6	5	34.25	6.85	9	51.9	5.77	10	53.5	5.35

Table 5: Effect of marginal decreasing rate variation for multiple products on bundle pricing decisions.

t	$\beta = 0.2$			$\beta = 0.5$			$\beta = 0.8$		
	BS (#unit)	BP ($/bundle)	BP/BS ($/unit)	BS (#unit)	BP ($/bundle)	BP/BS ($/unit)	BS (#unit)	BP ($/bundle)	BP/BS ($/unit)
1	10	86.5	8.65	8	60.9	7.61	6	43.5	7.26
2	4	33.9	8.48	6	47.8	7.97	4	32.0	7.99
3	2	17.0	8.50	2	16.7	8.35	2	16.4	8.20
4	6	48.18	8.03	1	8.2	8.20	3	23.2	7.72
5	10	66.8	6.68	7	46.97	6.71	3	22.1	7.38
6	10	62.0	6.20	9	51.9	5.77	3	21.2	7.05

diminishing marginal utility. Here, we use β to demonstrate the marginal decreasing rate. Practically, it can indicate whether a fresh product is proper to bundle with too many amounts. For example, compared with the apple, the durian is definitely not appropriate to bundle with too many amounts for its particular flavor and larger-size. And it will have a higher level of β. Results of changing in β are shown in Table 5. (1) It indicates that at the beginning and the end of life cycle, the larger-size bundles are preferred. It is consistent with the previous results. (2) However, the increase in β will definitely drop down the bundle size, whereas the unit product price will maintain a higher level. It can be explained intuitively that a product with higher marginal decreasing rate is suited for small size bundle. And the retailer can earn profit only if the price is set at a relatively higher level.

5. Conclusions

This study has investigated the bundle pricing problem for homogeneous fresh products with quality deterioration. The time value of fresh products has been approximated by using a lifecycle function, based on which the consumer reservation price has been formulated. Then, we have formulated the bundle pricing problem as a nonlinear mixed integer programming model. Next, the big M method has been used to linearize the nonlinear model, and the model has been converted into a linear one. Finally, we have carried out several numerical experiments to verify the efficiency and effectiveness of bundling pricing strategy. Numerical results demonstrated that the best time to bundle a larger number of fresh products was right after the beginning of the selling time and at the end of life cycle. Besides, the decrease in consumer heterogeneity and increase in deterioration rate would drop down the bundle size at a stable level in the whole life cycle of the fresh products. These findings can not only guide the grocery retailer to make price strategy and carry out the inventory and promotion activities on agriproducts, but also enrich the theoretical contributions in agricultural operations management.

A shortcoming of this work is lack of solution algorithm for the proposed model. We leave it in our future work. Besides, some potential research questions include the following areas. First, the combination with the technology of IOT (Internet of Things) to get the real-time data of fresh product quality is a direction to improve the practicability of the proposed model. Second, incorporating the logistics service into the proposed model is also worth further studying.

Conflicts of Interest

The authors declared that they have no conflicts of interest.

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References

[1] Fresh Supermarket Market Analysis and Industry Survey Report in China. Posted by BosiData on Oct. http://www.bosidata.com/news/167198KQTU.html [Accessed on 2017.1.12], 2016.

[2] Y. Yu and T. Xiao, "Pricing and cold-chain service level decisions in a fresh agri-products supply chain with logistics outsourcing," *Journal of Industrial Engineering*, vol. 111, pp. 56–66, 2017.

[3] Y. Qin, J. Wang, and C. Wei, "Joint pricing and inventory control for fresh produce and foods with quality and physical quantity deteriorating simultaneously," *International Journal of Production Economics*, vol. 152, pp. 42–48, 2014.

[4] G. J. Stigler, "United States v. Loew's inc.: a note on blockbooking," *The Supreme Court Review*, vol. 1963, pp. 152–157, 1963.

[5] Y. Jiang, J. Shang, C. F. Kemerer, and Y. Liu, "Optimizing E-tailer profits and customer savings: pricing multistage customized online bundles," *Marketing Science*, vol. 30, no. 4, pp. 737–752, 2011.

[6] A. Cataldo and J.-C. Ferrer, "Optimal pricing and composition of multiple bundles: a two-step approach," *European Journal of Operational Research*, vol. 259, no. 2, pp. 766–777, 2017.

[7] S. Mayer, R. Klein, and S. Seiermann, "A simulation-based approach to price optimisation of the mixed bundling problem with capacity constraints," *International Journal of Production Economics*, vol. 145, no. 2, pp. 584–598, 2013.

[8] X. Wang, Z. P. Fan, and Z. Liu, "Optimal markdown policy of perishable food under the consumer price fairness perception," *International Journal of Production Research*, vol. 54, no. 19, pp. 5811–5828, 2016.

[9] G. Liu, J. Zhang, and W. Tang, "Joint dynamic pricing and investment strategy for perishable foods with price-quality dependent demand," *Annals of Operations Research*, vol. 226, no. 1, pp. 397–416, 2015.

[10] X. Geng, M. B. Stinchcombe, and A. B. Whinston, "Bundling information goods of decreasing value," *Management Science*, vol. 51, no. 4, pp. 662–667, 2005.

[11] P. J. Liu, K. L. Haws, C. Lamberton, T. H. Campbell, and G. J. Fitzsimons, "Vice-virtue bundles," *Management Science*, vol. 61, no. 1, pp. 204–228, 2015.

[12] M. Sheikhzadeh and E. Elahi, "Product bundling: Impacts of product heterogeneity and risk considerations," *International Journal of Production Economics*, vol. 144, no. 1, pp. 209–222, 2013.

[13] E. T. Bradlow and V. R. Rao, "A hierarchical Bayes model for assortment choice," *Journal of Marketing Research*, vol. 37, no. 2, pp. 259–268, 2000.

[14] W. Hanson and R. K. Martin, "Optimal bundle pricing," *Management Science*, vol. 36, no. 2, pp. 155–174, 1990.

[15] R. Venkatesh and V. Mahajan, "The design and pricing of bundles: a review of normative guidelines and practical approaches," *Handbook of Pricing Research in Marketing*, pp. 232–257, 2009.

[16] S.-Y. Wu, L. M. Hitt, P.-Y. Chen, and G. Anandalingam, "Customized bundle pricing for information goods: a nonlinear mixed-integer programming approach," *Management Science*, vol. 54, no. 3, pp. 608–622, 2008.

[17] B. G. Hardie, E. J. Johnson, and P. S. Fader, "Modeling loss aversion and reference dependence effects on brand choice," *Marketing science*, vol. 12, no. 4, pp. 378–394, 1993.

[18] C.-Y. Dye and C.-T. Yang, "Optimal dynamic pricing and preservation technology investment for deteriorating products with reference price effects," *Omega*, vol. 62, pp. 52–67, 2016.

[19] R. Bai and G. Kendall, "A model for fresh produce shelf-space allocation and inventory management with freshness-condition-dependent demand," *INFORMS Journal on Computing*, vol. 20, no. 1, pp. 78–85, 2008.

[20] X. Wang and D. Li, "A dynamic product quality evaluation based pricing model for perishable food supply chains," *Omega*, vol. 40, no. 6, pp. 906–917, 2012.

[21] Y. Chen and G. Iyer, "Consumer addressability and customized pricing," *Marketing Science*, vol. 21, no. 2, pp. 197–208, 2002.

[22] A. Schrijver, *Theory of Linear and Integer Programming*, John Wiley & Sons, 1998.

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Research Article

Vertical Cost-Information Sharing in a Food Supply Chain with Multiple Unreliable Suppliers and Two Manufacturers

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This paper considers a food supply chain where multiple suppliers provide completely substitutable food products to two manufacturers. Meanwhile, the suppliers face yield uncertainty and the manufacturers face uncertain production costs that are private information. While the suppliers compete on price, the manufacturers compete on quantity. We build a stylized multistage game theoretic model to analyze the issue of vertical cost-information sharing (VCIS) within the supply chain by considering key parameters, including the level of yield uncertainty, two manufacturers' cost correlation, the correlated coefficient of suppliers' yield processes, and the number of suppliers. We study the suppliers' optimal wholesale price and the manufacturers' optimal order quantities under different VCIS strategies. Finally, through numerical analyses, we examine how key parameters affect the value of VCIS to each supplier and each manufacturer, respectively. We found that the manufacturers are willing to share cost information with suppliers only when the two manufacturers' cost correlation is less than a threshold. While a high correlated coefficient of suppliers' yield processes and a large number of suppliers promote complete information sharing, a high level of yield uncertainty hinders complete information sharing. All these findings have important implications to industry practices.

1. Introduction

Information asymmetry between supply chain (SC) members is a great challenge for food SC management. Information sharing is an effect tool to eliminate the impact of information asymmetry on SC partners' performances [1]. Demand information sharing [2] and cost-information sharing [3] have been much discussed by scholars. Most of literature assumed that the suppliers are reliable, while in industry practices the suppliers are unreliable due to various uncontrollable factors including equipment error and natural hazards. Our work focuses on vertical cost-information sharing by considering the suppliers with yield uncertainty.

Yield uncertainty is a popular phenomenon in the agricultural and food industries. The quality of agricultural and food products is very sensitive to temperature, humidity, and other natural conditions. For example, in agribusinesses, the yield of crop per acre is uncertain as it depends on such factors as climate condition, irrigation level, and so forth (http://nca2014.globalchange.gov/report/sectors/agriculture). Recently Recha et al. [4] have provided a symmetric report about the effect of climate-correlated conditions on food quality. Some scholars analyzed food SC management in different views. For example, Nyamah et al. [5] and MacKenzie and Apte [6] investigated food quality risk management from the operations management perspective. Keizer et al. [7] and Jin et al. [8] investigated food SC by considering supply network and food traceability, respectively. They examined food SC in a complete information situation, whereas in reality information asymmetry between upstream and downstream SC firms often exists.

After the sourcing firms (i.e., manufacturers) have received the product from farmers (i.e., suppliers), they process these products into final products with one unit marginal cost and sell in a common market. The marginal costs are also uncertain due to uncertain labor cost, uncertain storage costs, and other uncontrollable factors. Both supply uncertainty and cost uncertainty directly affect upstream and downstream SC firms' wholesale prices and order quantity decisions. In this paper, we consider that two manufacturers' costs are their private information.

Motivated by the real business situation as mentioned above, this paper examines a SC with multiple suppliers and two manufacturers and aims to answer two important questions. First, how do suppliers and manufacturers make decisions on wholesale prices and order quantities, respectively, under different VCIS scenarios? (2) Are manufacturers willing to disclose cost information to suppliers?

To answer the above questions, we build a classic three-stage game model. At the 1st-stage VCIS game, each manufacturer has two VCIS strategies: share and not share. Hence, there are four VCIS scenarios: (1) both manufacturers share cost information (i.e., complete cost-information sharing, CCIS); (2) none of them share cost information (i.e., no cost-information sharing, NCIS); (3) manufacturer 1 shares cost information, but manufacturer 2 does not; (4) manufacturer 2 shares cost information, but manufacturer 1 does not. The 2nd stage is the multiple suppliers' selling price game, and the 3rd stage is the two manufacturers' selling quantities game. After solving each subgame, we obtain the suppliers' optimal wholesale prices and the two manufacturers' optimal order quantities under each VCIS scenario. Further, we found that both manufacturers are willing to share cost information with their suppliers. Moreover, we found that complete information sharing will benefit all SC partners and the whole SC.

The remainder of this paper is as follows. Section 2 summarizes the related work. The model framework is shown in Section 3. The equilibrium solutions for four VCIS scenarios are provided in Section 4. The VCIS game is analyzed in Section 5. Section 6 provides a numerical analysis. Conclusions are drawn in Section 7.

2. Related Work

Our research is closely related to information sharing. The literature in this area can be divided into two streams: horizontal information sharing (HIS) and vertical information sharing (VIS) [9].

Some scholars focus on HIS. For example, Clarke [10] and Galor [11] studied HIS in an oligopoly model and showed that no HIS is a unique equilibrium. Kirby [12] investigated the incentive for HIS in an oligopoly model where firms have nonlinear product costs and showed that HIS exists under some conditions. Vives [13] discussed firms' HIS under Cournot competition and Bertrand competition, respectively. Li [14] examined the inventive for demand and cost-information sharing. Zhu [3] and Zhou and Zhu [15] investigated the incentive for cost-information sharing in a business-to-business setting under Cournot competition. Wu et al. [16] examined HIS by considering firms with capacity constraints. Natarajan et al. [17] analyzed HIS by considering time as an important factor in their model. Jiang and Hao [18] showed that information sharing and cooperative price for firms are strategic complements.

On the other hand, some researchers focus on VIS in a SC context. Li [19] and Zhang [20] took information leakage into account when studying VIS within a SC. Subsequently, Anand and Goyal [21], Kong et al. [22], and Shamir [23] investigated VIS by taking into account the fact that information leakage comes from the upstream suppliers. Li and Zhang [2] examined how the level of confidentiality influences firms' VIS decisions. Ha et al. [24, 25] studied VIS in two competing SCs. Wu et al. [26] examined the relationship between channel construction and VIS. Jiang and Hao [27] examined VIS under different channel structures. Subsequently, Zhou et al. [28] explored the effect of group purchasing organizations (GPOs) on VIS. Zhang and Xiong [29] explored VIS in a closed-loop SC. These papers focused on demand information sharing. Cost-information sharing has also been researched by several scholars. For example, Yao et al. [30] explored cost-information sharing in a SC by considering value-added costs as retailers' private information. Liu et al. [31] examined the interplay between VCIS and channel choices. Kostamis and Duenyas [32] investigated the value of both cost and demand information sharing. Moreover, Cachon and Lariviere [33], Eksoz et al. [34], and Resende-Filho and Hurley [35] explored the value of information to SC operational decisions.

Our work is different from those works above in that we examine the incentive for VCIS within a SC which has n-suppliers and two competing manufactures. The suppliers are subject to yield uncertainty and are engaged in setting price. Therefore, this is the first study to address the above-mentioned business scenario.

3. Model Framework

In this paper, we consider a SC with n unreliable suppliers and two competing manufacturers with private cost information. The suppliers sell complete substitutable food products to the two manufacturers.

3.1. Supply and Cost-Information Structures. The suppliers' yield uncertainty is modeled as a random proportion [36]; that is, if one manufacture's order quantity for each supplier is q_{ik}, the final quantity received from each supplier is a random proportion y_k of q_{ik}, that is, $y_k q_{ik}$. We assume that $y_k \in (0,1]$ and $E[y_k] = \mu \leq 1$ and $\mathrm{Var}[y_k] = \sigma_y^2$ (the same assumption is provided in [37–39]). Also, we assume that $\rho = \mathrm{Cov}(y_k, y_l)/\sigma_y^2$ and $\rho \in [-1, 1)$, $k \neq l$. In addition, let $\delta = \sigma_y/\mu$ denote the level of yield uncertainty. Each supplier's expected cost is c, where $c = c_1/\mu + c_2$ and c_1 and c_2 represent the unit manufacture cost and the unit transport cost, respectively.

Each manufacturer's marginal cost c_{m_i} is uncertain, and we assume that c_{m_i} follows a normal distribution with $E[c_{m_i}] = 0$ and $\mathrm{Var}[c_{m_i}] = \sigma^2$ [19]. It is also assumed that c_{m_i} and c_{m_j} satisfy the following: (1) $E[c_{m_i} \mid c_{m_j}] = \gamma_i + \gamma_j c_{m_j}$, where γ_i, γ_j are positive constants for all $j = 3-i$, $i = 1, 2$, and (2) c_{m_i} and c_{m_j} are identically distributed. Therefore, we have

$$E\left[c_{m_i} \mid c_{m_j}\right] = \eta c_{m_j};$$

$$E\left[c_{m_i} c_{m_j}\right] = \eta \sigma^2;$$

$$E\left[c_{m_i}c_{m_i}\right]=\sigma^2, \tag{1}$$

where $\eta=\mathrm{Cov}[c_{m_i}c_{m_j}]/\sigma^2$ and $\eta\in(0,1)$.

3.2. The Demand Function. Similar to [19, 40], we assume that the inverse demand function is

$$P=a-Q_i-Q_j,\quad j=3-i,\ i=1,2, \tag{2}$$

where a is demand intercept, P is the product's retail price, and Q_i and Q_j are the manufacturer i's and the manufacturer j's selling quantities in the common market.

3.3. Sequence Decisions Made by the Manufacturers and Suppliers. The sequence of decisions made by SC members is specified as follows:

(1) Each downstream SC member (i.e., manufacturer) decides whether to share the cost information with upstream SC members (i.e., suppliers) or not.

(2) The suppliers make a decision on prices.

(3) The manufacturers make a decision on selling quantities.

(4) The suppliers make production decisions and transport products.

(5) The yield and cost uncertainties are realized, and the demand is satisfied.

This is a three-stage game problem based on the above sequence. The 1st-stage game is VCIS game. Let $Z_i=Y$ ($Z_i=N$) which means that manufacturer i shares (or does not share) cost information with each supplier. Thus, there exists four possible VCIS scenarios in the 1st-stage game: (Y,Y), (N,N), (Y,N), and (N,Y). The other two games are the selling price game for the suppliers and the selling quantity game for the manufacturers.

The main variables that will be used in the paper are summarized in "Notation for Variables" section.

4. Equilibrium Solutions

In this section, because strategies (Y,N) and (N,Y) are symmetrical, we only consider strategy (Y,N). We address the manufacturers' optimal decisions q_{ik}^* and suppliers' optimal decisions w_k^* under three possible VCIS scenarios: (Y,Y), (N,N), and (Y,N).

4.1. Subgame (Y,Y): Both Manufacturers Share Cost Information. If both manufacturers choose VCIS, the suppliers can make an optimal decision based on c_{m_1} and c_{m_2}. One manufacturer can infer the other manufacturer's private cost information from w_k^{YY*} [19].

Therefore, under subgame (Y,Y), manufacturer i's ($i=1,2$) optimization problem is

$$\max_{q_{i1},q_{i1},\dots,q_{in}} E\left[\pi_{m_i}\mid c_{m_i},c_{m_j}\right]=E\left\{\left(a-\sum_{i=1}^{2}\sum_{k=1}^{n}y_kq_{ik}\right)\sum_{k=1}^{n}y_kq_{ik}-\sum_{k=1}^{n}w_ky_kq_{ik}-c_{m_i}\sum_{k=1}^{n}y_kq_{ik}\mid c_{m_i},c_{m_j}\right\}. \tag{3}$$

Supplier k's ($k=1,2,\dots,n$) optimization problem is

$$\max_{w_k}\ \left[\pi_{s_k}\mid c_{m_1},c_{m_2}\right]=E\left[\left(w_k-c\right)y_k\left(q_{1k}+q_{2k}\right)\mid c_{m_1},c_{m_2}\right]. \tag{4}$$

q_{ik}^{YY*} ($i=1,2,k=1,2,\dots,n$) should satisfy the following 1st-order condition:

$$q_{ik}^{YY*}=\frac{(a-w_k)}{2\mu(1-\rho)\delta_y^2}-\frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}(a-w_k)}{2\mu(1-\rho)\delta_y^2\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]}-\frac{1}{2\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]}\cdot E\left(c_{m_i}\mid c_{m_i},c_{m_j}\right)-\frac{1}{2}E\left(q_{jk}^{YY*}\mid c_{m_i},c_{m_j}\right). \tag{5}$$

By Proposition 1 in [14], the unique equilibrium solutions for the manufacturers are specified as

$$q_{ik}^{YY*}=\frac{(a-w_k)}{3\mu(1-\rho)\delta_y^2}-\frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}(a-w_k)}{3\mu(1-\rho)\delta_y^2\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]}-\frac{2}{3\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]}c_{m_i}+\frac{1}{3\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]}c_{m_j}. \tag{6}$$

By inserting q_{ik}^{YY*} into (4), we obtain w_k^{YY*} ($k=1,2,\dots,n$) which should satisfy the following 1st-order condition:

$$w_k^{YY*} = \frac{a+c}{2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{l\neq k}^{n}\left[a - E\left(w_l \mid c_{m_1}, c_{m_2}\right)\right]}{2\left[(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]} - \frac{(1-\rho)\delta_y^2}{4\left[(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]}\left(c_{m_1} + c_{m_2}\right). \quad (7)$$

Based on Proposition 1 in [14], there exist unique equilibrium solutions w_k^{YY*}. By substituting w_k^{YY*} into (5) and simplifying, we obtain Proposition 1.

Proposition 1. *The equilibrium solutions for subgame* (Y, Y) *are specified as follows.*

(1) The optimal decisions for the suppliers at equilibrium are

$$w_k^{YY*} = \overline{w}_k + \xi_{k1}^{YY} c_{m_1} + \xi_{k2}^{YY} c_{m_2}, \quad (8)$$

where

$$\overline{w}_k = \frac{(1-\rho)\delta_y^2 a + \left[(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]c}{\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]},$$
$$\xi_{k1}^{YY} = \xi_{k2}^{YY} = -\frac{(1-\rho)\delta_y^2}{2\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]}. \quad (9)$$

(2) The optimal decisions for the manufacturers at equilibrium are

$$q_{ik}^{YY*} = \overline{q}_{ik} + f_{iki}^{YY} c_{m_i} + f_{ikj}^{YY} c_{m_j}, \quad (10)$$

where

$$\overline{q}_{ik} = \frac{\left[(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right](a-c)}{3\mu\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]},$$
$$f_{iki}^{YY} = -\frac{\left[7(1-\rho)\delta_y^2 + 4(n-1)\left(1+\rho\delta_y^2\right)\right]}{6\mu\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]},$$
$$f_{ikj}^{YY} = \frac{\left[5(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)\right]}{6\mu\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]}. \quad (11)$$

In Proposition 1, both w_k^{YY*} and q_{ik}^{YY*} are composed of two parts: one is not dependent on c_{m_i} and c_{m_j} (i.e., $\overline{w}_k$ and $\overline{q}_{ik}$), while the other is dependent on c_{m_i} and c_{m_j} (i.e., $\xi_{k1}^{YY} c_{m_1} + \xi_{k2}^{YY} c_{m_2}$ and $f_{ii}^{YY} c_{m_i} + f_{ij}^{YY} c_{m_j}$). Clearly, $\xi_{k1}^{YY} = \xi_{k2}^{YY} < 0$, $f_{iki}^{YY} < 0$, and $f_{ikj}^{YY} > 0$. $\xi_{k1}^{YY} = \xi_{k2}^{YY} < 0$ means that w_k^{YY*} is negatively related to $c_{m_i} + c_{m_j}$. $f_{iki}^{YY} < 0$ means that q_{ik}^{YY*} responds negatively to c_{m_i}, and $f_{ikj}^{YY} > 0$ shows that q_{ik}^{YY*} is positively related to c_{m_j}.

4.2. Subgame (N, N)*: No Manufacturer Shares Cost Information.* Suppose that no manufacturer shares private cost information with their suppliers. The suppliers' optimal decisions w_k^{NN*} are independent of the manufacturers' cost information. Therefore, one manufacturer cannot infer the other firm's cost information from w_k^{NN*} [19].

Therefore, under subgame (N, N), the manufacturer i's $(i = 1, 2)$ optimization problem is

$$\max_{q_{i1}, q_{i1}, \ldots, q_{in}} E\left[\pi_{m_i} \mid c_{m_i}\right] = E\left\{\left(a - \sum_{i=1}^{2}\sum_{k=1}^{n} y_k q_{ik}\right)\sum_{k=1}^{n} y_k q_{ik} - \sum_{k=1}^{n} w_k y_k q_{ik} - c_{m_i}\sum_{k=1}^{n} y_k q_{ik} \mid c_{m_i}\right\}. \quad (12)$$

Supplier k's $(k = 1, 2, \ldots, n)$ optimization problem is

$$\max_{w_k} \left[\pi_{s_k}\right] = E\left[\left(w_k - c\right) y_k \left(q_{1k} + q_{2k}\right)\right]. \quad (13)$$

Manufacturer i's optimal order quantities q_{ik}^{NN*} $(i = 1, 2,\ k = 1, 2, \ldots, n)$ should satisfy the following 1st-order condition:

$$q_{ik}^{NN*} = \frac{\left(a - w_k\right)}{2\mu(1-\rho)\delta_y^2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}\left(a - w_k\right)}{2\mu(1-\rho)\delta_y^2\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]}$$

$$-\frac{1}{2\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]}E\left(c_{m_i}\mid c_{m_i}\right)-\frac{1}{2}E\left(q_{jk}^{NN*}\mid c_{m_i}\right). \quad (14)$$

With reference to Proposition 1 in [14], the unique equilibrium solutions for the manufacturers are specified as

$$q_{ik}^{NN*}=\frac{(a-w_k)}{3\mu(1-\rho)\delta_y^2}-\frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}(a-w_k)}{3\mu(1-\rho)\delta_y^2\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]}-\frac{(1+t)}{\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right][2(1+t)+1]}\cdot c_{m_i}. \quad (15)$$

By inserting q_{ik}^{NN*} into (13), we can obtain the supplier's optimal wholesale price w_k^{NN*} $(k=1,2,\ldots,n)$ which satisfies the following 1st-order condition:

$$w_k^{NN*}=\frac{a+c}{2}-\frac{\left(1+\rho\delta_y^2\right)\sum_{l\neq k}^{n}\left(a-w_l^{NN*}\right)}{2\left[(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]}. \quad (16)$$

Based on Proposition 1 in [14], there exist unique equilibrium solutions w_k^{NN*} for the manufacturers. Substituting w_k^{NN*} into (13) and simplifying, we obtain Proposition 2.

Proposition 2. *The equilibrium solutions for subgame (N,N) are specified as follows.*

(1) The optimal decisions for the suppliers at equilibrium are

$$w_k^{NN*}=\overline{w}_k. \quad (17)$$

(2) The optimal decisions for the manufacturers at equilibrium are

$$q_{ik}^{NN*}=\overline{q}_{ik}+f_{iki}^{NN}c_{m_i}, \quad (18)$$

where

$$f_{iki}^{NN}=-\frac{1}{\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right](2+\eta)}. \quad (19)$$

Proposition 2 shows that the suppliers' optimal decisions are independent of the manufacturers' private cost information, and manufacturer i's optimal decision depends only on c_{m_i}. $f_{iki}^{NN}<0$ indicates that manufacturer i responds negatively to c_{m_i}.

4.3. Subgame (Y,N): Only One Manufacturer Shares Cost Information. Suppose only manufacturer 1 shares cost information c_{m_1} with their suppliers. The suppliers set w_k^{SN*} based on c_{m_1}. Then manufacturer 2 can infer manufacturer 1's cost information from w_k^{SN*} [19].

Therefore, under subgame (Y,N), manufacturer 1's optimization problem is

$$\max_{q_{11},q_{11},\ldots,q_{1n}} E\left[\pi_{m_1}\mid c_{m_1}\right]=E\left\{\left(a-\sum_{i=1}^{2}\sum_{k=1}^{n}y_kq_{1k}\right)\sum_{k=1}^{n}y_kq_{1k}-\sum_{k=1}^{n}w_ky_kq_{1k}-c_{m_1}\sum_{k=1}^{n}y_kq_{1k}\mid c_{m_1}\right\}. \quad (20)$$

Manufacturer 2's optimization problem is

$$\max_{q_{21},q_{21},\ldots,q_{2n}} E\left[\pi_{m_2}\mid c_{m_1},c_{m_2}\right]=E\left\{\left(a-\sum_{i=1}^{2}\sum_{k=1}^{n}y_kq_{2k}\right)\sum_{k=1}^{n}y_kq_{2k}-\sum_{k=1}^{n}w_ky_kq_{2k}-c_{m_2}\sum_{k=1}^{n}y_kq_{2k}\mid c_{m_1},c_{m_2}\right\}. \quad (21)$$

Supplier k's $(k=1,2,\ldots,n)$ optimization problem is

$$\max_{w_k}\left[\pi_{s_k}\mid c_{m_1}\right]=E\left[(w_k-c)y_k(q_{1k}+q_{2k})\mid c_{m_1}\right]. \quad (22)$$

The two manufacturers' optimal order quantities q_{1k}^{YN*} and q_{2k}^{YN*} $(k=1,2,\ldots,n)$ should satisfy the following 1st-order condition:

$$q_{1k}^{YN*}=\frac{(a-w_k)}{2\mu(1-\rho)\delta_y^2}-\frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}(a-w_k)}{2\mu(1-\rho)\delta_y^2\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]}-\frac{1}{2\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]}E\left(c_{m_1}\mid c_{m_1}\right)-\frac{1}{2}E\left(q_{2k}^{YN*}\mid c_{m_1}\right),$$

$$q_{2k}^{YN*}=\frac{(a-w_k)}{2\mu(1-\rho)\delta_y^2}$$

$$-\frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}\left(a-w_k\right)}{2\mu\left(1-\rho\right)\delta_y^2\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} - \frac{1}{2\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} \cdot E\left(c_{m_2}\mid c_{m_1},c_{m_2}\right)-\frac{1}{2}E\left(q_{1k}^{YN*}\mid c_{m_1},c_{m_2}\right). \quad (23)$$

With reference to Proposition 1 in [14], the unique equilibrium solutions for the two manufacturers are presented as follows:

$$q_{1k}^{YN*} = \frac{\left(a-w_k\right)}{3\mu\left(1-\rho\right)\delta_y^2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}\left(a-w_k\right)}{3\mu\left(1-\rho\right)\delta_y^2\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} + \frac{\eta-2}{3\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}c_{m_1}, \quad (24)$$

$$q_{2k}^{YN*} = \frac{\left(a-w_k\right)}{3\mu\left(1-\rho\right)\delta_y^2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}\left(a-w_k\right)}{3\mu\left(1-\rho\right)\delta_y^2\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} + \frac{2-\eta}{6\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}c_{m_1} - \frac{1}{2\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}c_{m_2}. \quad (25)$$

By substituting q_{1k}^{YN*} and q_{2k}^{YN*} into (22), we can obtain the suppliers' optimal wholesale price w_k^{YN*} $(k=1,2,\ldots,n)$ that satisfies the following 1st-order condition:

$$w_k^{YN*} = \frac{a+c}{2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{l\neq k}^{n}\left(a-w_l^{YN*}\right)}{2\left[\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} - \frac{\left(1-\rho\right)\delta_y^2\left(\eta+1\right)}{4\left[\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}c_{m_1}. \quad (26)$$

Based on Proposition 1 in [14], there exist unique equilibrium solutions w_k^{YN*} for two manufacturers. By substituting w_k^{YN*} into (24) and (25), respectively, and simplifying, we obtain Proposition 3.

Proposition 3. *The equilibrium solutions for subgame* (Y,N) *are specified as follows.*

(1) The optimal decisions for the suppliers at equilibrium are

$$w_k^{YN*} = \overline{w}_k + \xi_{k1}^{YN}c_{m_1}, \quad (27)$$

where

$$\xi_{k1}^{YN} = -\frac{\left(1-\rho\right)\delta_y^2\left(\eta+1\right)}{2\left[2\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}. \quad (28)$$

(2) The optimal decisions for the manufacturers at equilibrium are

$$q_{1k}^{YN*} = \overline{q}_{1k} + f_{1k1}^{YN}c_{m_1},$$
$$q_{2k}^{YN*} = \overline{q}_{2k} + f_{2k1}^{YN}c_{m_1} + f_{2k2}^{YN}c_{m_2}, \quad (29)$$

where

$$f_{1k1}^{YN} = \frac{\left[5\left(1-\rho\right)\delta_y^2+2\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\eta-\left[7\left(1-\rho\right)\delta_y^2+4\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}{6\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\left[2\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]},$$
$$f_{2k1}^{YN} = \frac{\left[5\left(1-\rho\right)\delta_y^2+2\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]-\left[\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\eta}{6\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\left[2\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}, \quad (30)$$
$$f_{2k2}^{YN} = -\frac{1}{2\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}.$$

Proposition 3 indicates that both the suppliers and manufacturer 1's optimal decisions only depend on c_{m_1}, while manufacturer 2's optimal decision depends on both c_{m_1} and c_{m_2}. This is because manufacturer 2 can infer manufacturer 1's cost information from w_k^{YN*}, while manufacturer 1 cannot infer manufacturer 2's cost information from w_k^{YN*}. $\xi_{k1}^{YN}<0$, $f_{iki}^{YN}<0$, and $f_{jkj}^{YN}<0$, respectively, indicate that the suppliers, manufacturer 1, and manufacturer 2 respond negatively to c_{m_1}, c_{m_1}, and c_{m_2}. Moreover, f_{2k1}^{YN} negatively or positively depends on the value of key parameters: δ_y, ρ, and

t. When $[5(1-\rho)\delta_y^2 + 2(n-1)(1+\rho\delta_y^2)] < [(1-\rho)\delta_y^2 + (n-1)(1+\rho\delta_y^2)]\eta$, manufacturer 2 responds negatively to c_{m_1}, while manufacturer 2 responds positively to c_{m_1}.

All information from Propositions 1–3 is valuable to the suppliers and manufacturers in determining their wholesale prices and order quantities.

5. Information Sharing Game

We first calculate the suppliers and manufacturers' ex ante payoffs based on the equilibrium solutions for any pair of VCIS strategies and summarize the results in Table 1. Subsequently, we solve the cost-information sharing game.

Next, we analyze how manufacturers' VCIS affects each supplier by comparing SC partners' ex ante payoffs under strategy (Y, N) with (N, N) and comparing SC partners' ex ante payoffs under strategy (Y, Y) with (N, Y).

Proposition 4. *The SC members' ex ante payoffs have the following properties.*

(1) $\pi_{s_k}^{YY*} > \pi_{s_k}^{YN*} > \pi_{s_k}^{NN*}$.

(2) (a) $\pi_{m_1}^{YY*} > \pi_{m_1}^{NY*}$; (b) if $0 < \eta < \eta_1$, $\pi_{m_1}^{YN*} > \pi_{m_1}^{NN*}$; if $1 \geq \eta > \eta_1$, $\pi_{m_1}^{YN*} < \pi_{m_1}^{NN*}$, where

$$\eta_1 = \frac{2(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)}{5(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)}. \tag{31}$$

(3) (a) $\Pi_{m_2}^{YY*} > \pi_{m_2}^{NY*}$; (b) if $\varphi(n,\rho,\delta_y) > \psi(n,\rho,\delta_y,\eta)$, $\pi_{m_2}^{YN*} > \Pi_{m_2}^{NN*}$; if $\varphi(n,\rho,\delta_y) < \psi(n,\rho,\delta_y,\eta)$, $\pi_{m_2}^{YN*} < \Pi_{m_2}^{NN*}$, where

$$\begin{aligned}
\varphi\left(n,\rho,\delta_y\right) &= \frac{n\left[5(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2 + 9n\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2}, \\
\psi\left(n,\rho,\delta_y,\eta\right) &= \frac{n\left[7(1-\rho)\delta_y^2 + 4(n-1)\left(1+\rho\delta_y^2\right)\right]\left[5(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)\right]\eta\sigma_c^2}{18\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\
&\quad - \frac{n\left[(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[13(1-\rho)\delta_y^2 + 7(n-1)\left(1+\rho\delta_y^2\right)\right]\eta^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\
&\quad + \frac{n\sigma_c^2}{\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right](2+\eta)^2}.
\end{aligned} \tag{32}$$

Proof. See Appendix. □

Proposition 4 Part (1) means that the suppliers will gain more ex ante payoffs from more manufacturers disclosing their private cost information.

Proposition 4 Part (2) shows that CCIS and NCIS are two possible equilibrium solutions for the two manufacturers. The manufacturers always agree to VCIS when the correlated coefficient of two manufacturers' cost uncertainty is less than a threshold (i.e., $0 < \eta < \eta_1$).

Proposition 4 Part (3) states that a manufacturer does not always benefit from its competitor manufacturer's information sharing. If a manufacturer does not agree to VCIS, it benefits from the competitor manufacturer's VCIS only when $\varphi(n,\rho,\delta_y) > \psi(n,\rho,\delta_y,\eta)$.

Proposition 5. *Complete cost-information sharing Pareto-dominates no cost-information sharing.*

Proof. See Appendix. □

Proposition 5 suggests that the entire SC's ex ante payoff with CCIS is larger than NCIS.

6. Numerical Analysis

In this section, we examine the impact of key parameters on the value of information sharing. As the two manufacturers are symmetric, we only focus on the value of information sharing by manufacturer 1. Let $V_{s_k}^N = \Pi_{s_k}^{YN*} - \Pi_{s_k}^{NN*}$, $V_{m_2}^N = \Pi_{m_2}^{YN*} - \Pi_{m_2}^{NN*}$, and $V_{m_1}^N = \Pi_{m_1}^{YN*} - \Pi_{m_1}^{NN*}$, respectively, represent the effect of manufacturer 1's information sharing to each supplier, manufacturer 2, and manufacturer 1. Similarly, let $V_{s_k}^Y = \Pi_{s_k}^{YY*} - \Pi_{s_k}^{NY*}$, $V_{m_2}^Y = \Pi_{m_2}^{YY*} - \Pi_{m_2}^{NY*}$, and $V_{m_1}^Y = \Pi_{m_1}^{YY*} - \Pi_{m_1}^{NY*}$, respectively, denote the effect of manufacturer 1 information sharing on SC partners' ex ante payoffs.

We assume the following: $\sigma_\theta^2 = 2$, $\rho = 0.5$, $\delta_y = 0.5$, $\eta = 0.7$, and $n = 2$. The effects of ρ, δ_y, η, and n on $V_{s_k}^N$, $V_{m_2}^N$, $V_{m_1}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$ are provided in Figures 1–4, respectively.

Figures 1(a) and 1(b) show that as ρ increases, $V_{s_k}^N$ and $V_{s_k}^Y$ decreases. It means that, whether manufacture 2 shares information or not, the higher ρ is, the less each supplier benefits from information sharing by manufacturer 1.

Figures 1(c) and 1(d) show that as ρ increases, $V_{m_2}^N$ increases, while $V_{m_2}^Y$ decreases. This shows that if manufacture

Table 1: The manufacturers' and suppliers' ex ante payoffs.

Subgame	The suppliers	The manufacturers
(Y, Y)	$\Pi_{s_k}^{YY*} = \overline{\Pi}_{s_k} + \dfrac{WR(\eta+1)\sigma_c^2}{3BC^2}$	$\Pi_{m_i}^{YY*} = \overline{\Pi}_{m_i} + \dfrac{n(U^2+T^2)\sigma_c^2}{36BC^2} - \dfrac{nUT\eta\sigma_c^2}{18BC^2}$
(N, N)	$\Pi_{s_k}^{NN*} = \overline{\Pi}_{s_k}$	$\Pi_{m_i}^{NN*} = \overline{\Pi}_{m_i} + \dfrac{n\sigma_c^2}{B(2+\eta)^2}$
(Y, N)	$\Pi_{s_k}^{YN*} = \overline{\Pi}_{s_k} + \dfrac{WR(\eta+1)^2\sigma_c^2}{6BC^2}$	$\Pi_{m_1}^{YN*} = \overline{\Pi}_{m_i} + \dfrac{n(\eta T-U)^2}{36BC^2}\sigma_c^2$ $\Pi_{m_2}^{YN*} = \overline{\Pi}_{m_i} + \dfrac{n(T-\eta R)^2\sigma_c^2}{36BC^2} + \dfrac{n\sigma_c^2}{4B} - \dfrac{n\eta(T-\eta R)\sigma_c^2}{6BC}$
(N, Y)	$\Pi_{s_k}^{NY*} = \overline{\Pi}_{s_k} + \dfrac{WR(\eta+1)^2\sigma_c^2}{6BC^2}$	$\Pi_{m_1}^{NY*} = \overline{\Pi}_{m_1} + \dfrac{n(T-\eta R)^2\sigma_c^2}{36BC^2} + \dfrac{n\sigma_c^2}{4B} - \dfrac{n\eta(T-\eta R)\sigma_c^2}{6BC}$ $\Pi_{m_2}^{NY*} = \overline{\Pi}_{m_2} + \dfrac{n(\eta T-U)^2\sigma_c^2}{36BC^2}$

Notes. $\overline{\Pi}_{m_i} = (nR^2/9BC^2)(a-c)^2$ and $\overline{\Pi}_{s_k} = (2(1-\rho)\delta_y^2 R/3BC^2)(a-c)^2$, $i = 1, 2$, $k = 1, 2, \dots, n$; $B = (1+\delta_y^2) + (n-1)(1+\rho\delta_y^2)$ and $C = 2(1-\rho)\delta_y^2 + (n-1)(1+\rho\delta_y^2)$; $R = (1-\rho)\delta_y^2 + (n-1)(1+\rho\delta_y^2)$ and $T = 5(1-\rho)\delta_y^2 + 2(n-1)(1+\rho\delta_y^2)$; $U = 7(1-\rho)\delta_y^2 + 4(n-1)(1+\rho\delta_y^2)$ and $W = (1-\rho)\delta_y^2$.

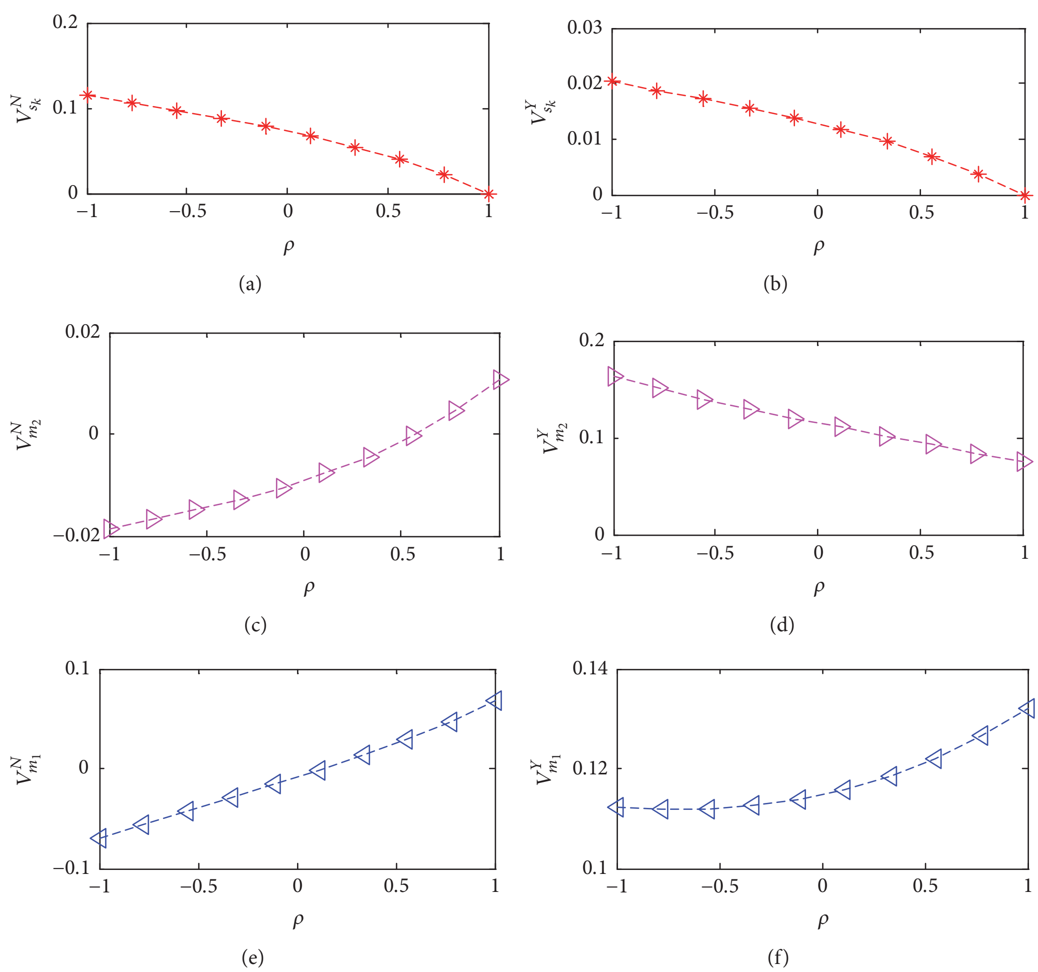

Figure 1: The effect of ρ on $V_{s_k}^N$, $V_{m_2}^N$, $V_{m_1}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$.

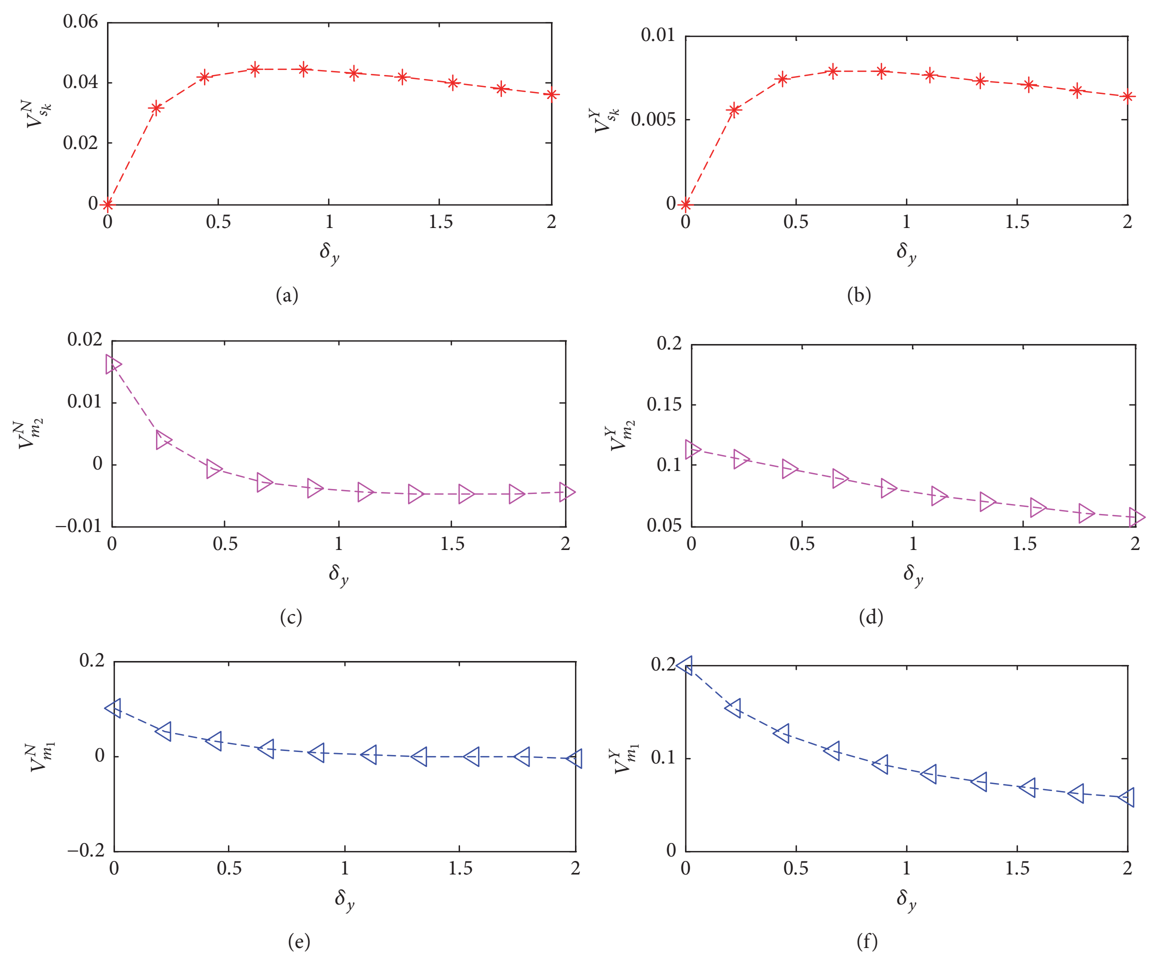

FIGURE 2: The impact of δ_y on $V_{s_k}^N$, $V_{m_2}^N$, $V_{m_1}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$.

2 agrees to VCIS, high ρ increases manufacturer 2's benefits from manufacturer 1's VCIS. If it does not agree to VCIS, high ρ reduces manufacturer 2's benefits from manufacturer 1's VCIS.

Figures 1(e) and 1(f) show that both $V_{m_1}^N$ and $V_{m_1}^Y$ increase with ρ. These mean that high ρ increases the value of information sharing by manufacturer 1 to itself.

Figures 2(a) and 2(b) show that as δ_y increases, both of $V_{s_k}^N$ and $V_{s_k}^Y$ first increase and then decrease. This indicates that the impacts of δ_y on $V_{s_k}^N$ and $V_{s_k}^Y$ are in the same direction.

Figures 2(c)–2(f) show that as δ_y increases, $V_{m_2}^N$, $V_{m_2}^Y$, $V_{m_1}^N$, and $V_{m_1}^Y$ decrease. This means that high δ_y will decrease the value of information sharing by manufacturer 1 to both manufacturer 1 and manufacturer 2.

Figures 3(a) and 3(b) show that $V_{s_k}^N$ increases with η, while $V_{s_k}^Y$ decreases with η. This means that given the fact that manufacture 2 decides not to disclose its cost information to its suppliers, high η promotes manufacturer 2's benefit when manufacturer 1 shares its cost information. If manufacture 2 decides to disclose its private cost information to its suppliers, high ρ decreases manufacturer 2's benefit when manufacturer 1 shares its cost information.

Figures 3(c)–3(f) show that as η increases, $V_{m_2}^N$, $V_{m_2}^Y$, $V_{m_1}^N$, and $V_{m_1}^Y$ decrease. It means that no matter whether manufacturer 2 decides to disclose cost information to suppliers or not, the value of information sharing by manufacturer 1 to both manufacturer 1 and manufacturer 2 decreases with η.

Figures 4(a) and 4(b) show that $V_{s_k}^N$ and $V_{s_k}^Y$ decrease with n. Figures 4(e) and 4(f) show that $V_{m_1}^N$ and $V_{m_1}^Y$ increase with n. It means that as the number of suppliers increases, each supplier benefits less from information sharing by manufacturer 1, while manufacturer 1 benefits more from information sharing by itself.

Figures 4(c) and 4(d) show that as n increases, $V_{m_2}^N$ increases while $V_{m_2}^Y$ decreases. It means that as the number of suppliers increases, the value of information sharing by manufacturer 1 is determined by manufacturer 2's information sharing strategy.

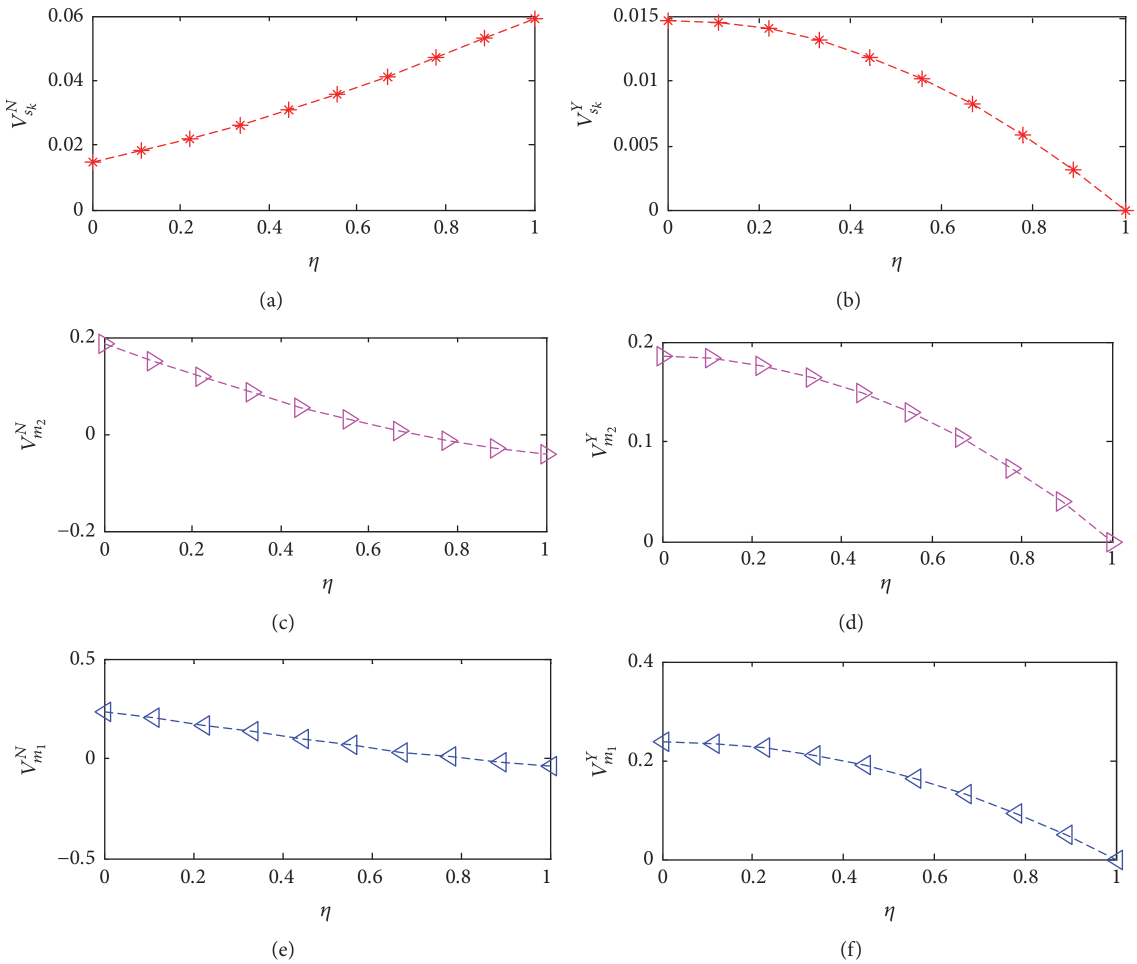

Figure 3: The impact of η on $V_{s_k}^N$, $V_{m_2}^N$, $V_{m_1}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$.

Figures 1–4 show that $V_{s_k}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$ are positive. Whether $V_{m_2}^N$ and $V_{m_1}^N$ are positive or negative is determined by the value of key parameters. $V_{m_1}^Y > 0$ indicates that if manufacturer 2 chooses to disclose its cost information to suppliers, manufacturer 1 will also reveal its cost information to suppliers. $V_{m_1}^N < 0$ suggests that given the fact that manufacturer 2 does not share information with suppliers, neither will manufacturer 1 with its own suppliers.

Moreover, we found that if manufacturer 1 shares its cost information, higher ρ means that manufacturer 1 would be more willing to share information (see Figure 1(f)), promoting complete information sharing. Similarly, higher n also promotes complete information sharing (see Figure 4(f)). However, higher δ_y and η undermine complete information sharing (see Figures 2(f) and 3(f)).

7. Conclusions

Information sharing is a hot topic in the literature of SC management. This study examines VCIS in a simplified SC which consists of two manufacturers with private cost information and n suppliers with yield uncertainty.

This work contributes to the area of research on incentive for VCIS. We analyze VCIS by considering the number of suppliers, the correlated coefficient of manufacturers' cost uncertainty, and the level of yield uncertainty and the correlated coefficient of the supply processes. We found that there exists only two equilibrium information sharing strategies: complete cost-information sharing and no cost-information sharing. The manufactures always agree to VCIS when the correlated coefficient of two manufacturers' cost uncertainty is less than a threshold. In addition, complete cost-information sharing will increase each supplier, each manufacturer, and the entire SC's ex ante payoffs when two manufacturers' cost uncertainty is less correlated. It suggests that the manufactures decide to perform VCIS.

This presented study can be further extended along the following three directions. First, other types of contract (e.g., two-part pricing contract) can be considered. Second, multiple manufacturers could be introduced to examine how the number of manufacturers affects the manufacturers' willingness to share information. Finally, our model could be expanded to include other types of competition such as newsvendor competition models.

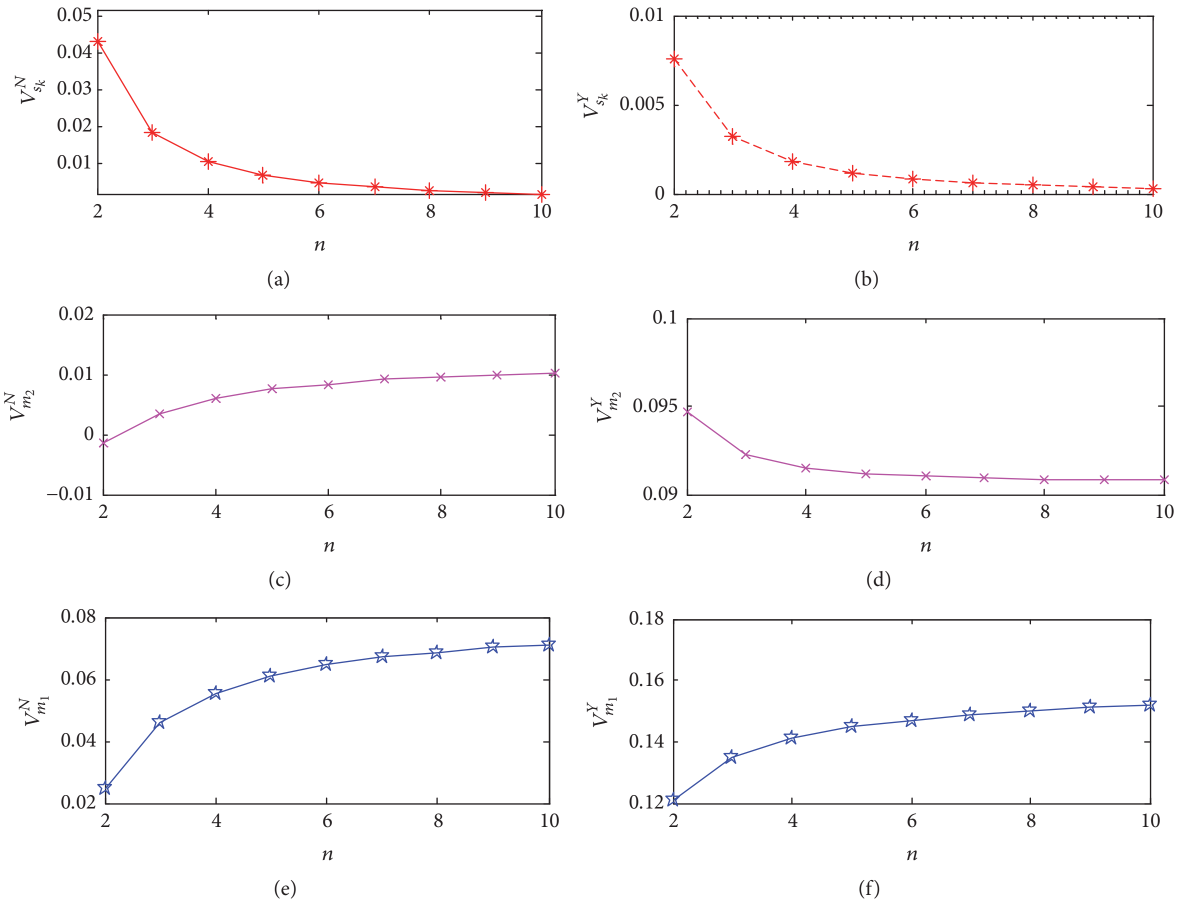

Figure 4: The impact of n on $V_{s_k}^N$, $V_{m_2}^N$, $V_{m_1}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$.

Appendix

Proof of Proposition 4. From Table 1, we have

$$\Pi_{s_k}^{YN*} - \Pi_{s_k}^{NN*} = \frac{(1-\rho)\,\delta_y^2\left[(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right](\eta+1)^2\,\sigma_c^2}{6\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\,\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} > 0, \tag{A.1}$$

$$\Pi_{s_k}^{YY*} - \Pi_{s_k}^{YN*} = \frac{(1-\rho)\,\delta_y^2\left[(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]\left(1-\eta^2\right)\sigma_c^2}{6\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\,\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} > 0, \tag{A.2}$$

$$\begin{aligned}
&\Pi_{m_2}^{YN*} - \Pi_{m_2}^{NN*} \\
&= \frac{n\left[5(1-\rho)\,\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2 + 9n\left[2(1-\rho)\,\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\,\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\
&\quad + \frac{n\left[(1-\rho)\,\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[13(1-\rho)\,\delta_y^2+7(n-1)\left(1+\rho\delta_y^2\right)\right]\eta^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\,\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\
&\quad - \frac{n\left[7(1-\rho)\,\delta_y^2+4(n-1)\left(1+\rho\delta_y^2\right)\right]\left[5(1-\rho)\,\delta_y^2+2(n-1)\left(1+\rho\delta_y^2\right)\right]\eta\sigma_c^2}{18\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\,\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} - \frac{n\sigma_c^2}{\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right](2+\eta)^2},
\end{aligned} \tag{A.3}$$

$$\Pi_{m_2}^{YY*} - \pi_{m_2}^{NY*} = \frac{n\left[5(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)\right]^2\left(1-\eta^2\right)\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} > 0, \tag{A.4}$$

$$\pi_{m_1}^{YN*} - \pi_{m_1}^{NN*} = \frac{-n\left\{(1-\rho)\delta_y^2\left(26-3\eta-5\eta^2\right)+2(n-1)\left(1+\rho\delta_y^2\right)\left(7-\eta^2\right)\right\}\cdot\left\{3(1-\rho)\delta_y^2\eta-2\left[(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right](1-\eta)\right\}(1+\eta)\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2(2+\eta)^2}, \tag{A.5}$$

$$\pi_{m_1}^{YY*} - \pi_{m_1}^{NY*} = \frac{n\left[(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[13(1-\rho)\delta_y^2+7(n-1)\left(1+\rho\delta_y^2\right)\right]\left(1-\eta^2\right)\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} > 0. \tag{A.6}$$

In (A.3), let $\Pi_{m_2}^{YN*} - \Pi_{m_2}^{NN*} = 0$, and we obtain $\varphi(n,\rho,\delta_y) = \psi(n,\rho,\delta_y,\eta)$, where

$$\varphi\left(n,\rho,\delta_y\right) = \frac{n\left[5(1-\rho)\delta_y^2+2(n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2 + 9n\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2}, \tag{A.7}$$

$$\begin{aligned}\psi\left(n,\rho,\delta_y,\eta\right) = {} & \frac{n\left[7(1-\rho)\delta_y^2+4(n-1)\left(1+\rho\delta_y^2\right)\right]\left[5(1-\rho)\delta_y^2+2(n-1)\left(1+\rho\delta_y^2\right)\right]\eta\sigma_c^2}{18\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\ & - \frac{n\left[(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[13(1-\rho)\delta_y^2+7(n-1)\left(1+\rho\delta_y^2\right)\right]\eta^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\ & + \frac{n\sigma_c^2}{\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right](2+\eta)^2}.\end{aligned} \tag{A.8}$$

In (A.5), let $\pi_{m_1}^{YN*} - \pi_{m_1}^{NN*} = 0$, and we obtain $\eta = \eta_1$, where

$$\eta_1 = \frac{2(1-\rho)\delta_y^2+2(n-1)\left(1+\rho\delta_y^2\right)}{5(1-\rho)\delta_y^2+2(n-1)\left(1+\rho\delta_y^2\right)}. \tag{A.9}$$

Thus, we have

(1) $\pi_{s_k}^{YY*} > \pi_{s_k}^{YN*} > \pi_{s_k}^{NN*}$.

(2) (a) $\pi_{m_1}^{YY*} > \pi_{m_1}^{NY*}$; (b) if $\eta < \eta_1$, $\pi_{m_1}^{YN*} > \pi_{m_1}^{NN*}$; if $\eta > \eta_1$, $\pi_{m_1}^{YN*} < \pi_{m_1}^{NN*}$.

(3) (a) $\Pi_{m_2}^{YY*} > \pi_{m_2}^{NY*}$; (b) if $\varphi(n,\rho,\delta_y) > \psi(n,\rho,\delta_y,\eta)$, $\pi_{m_2}^{YN*} > \Pi_{m_2}^{NN*}$; if $\varphi(n,\rho,\delta_y) < \psi(n,\rho,\delta_y,\eta)$, $\pi_{m_2}^{YN*} < \Pi_{m_2}^{NN*}$.

The proof of Proposition 4 is finished. □

Proof of Proposition 5. From Table 1, we obtain

$$\begin{aligned}\Pi^{YY*} - \Pi^{NN*} &= \left(\pi_{m_1}^{YY*} + \pi_{m_2}^{YY*} + n\pi_{s_k}^{YY*}\right) - \left(\Pi_{m_1}^{NN*} + \Pi_{m_2}^{NN*} + n\Pi_{s_k}^{NN*}\right) = \left(n\left\{2\left[4(1-\rho)^2\delta_y^4 + (n-1)^2\left(1+\rho\delta_y^2\right)^2\right]\left[30\eta^2 + 37\eta(1-\eta) + 11(1-\eta)^2\right](1-\eta) + (n-1)(1-\rho)\delta_y^2\left(1 + \rho\delta_y^2\right)\left[18\eta^3 + 273\eta^2(1-\eta) + 316\eta(1-\eta)^2 + 92(1-\eta)^3\right]\right\}\left(1/\eta^2\right)\sigma_c^2\right)\left(9\left[\left(1+\delta_y^2\right)+(n-1)\cdot\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2\cdot(3+2t)^2\right)^{-1} > 0.\end{aligned} \tag{A.10}$$

The proof of Proposition 5 is finished. □

Notation for Variables

w_k, q_{ik}:	Wholesale price and order quantity (decision variable)
π_{s_k}, π_{r_i}:	Supplier k's and manufacturer i's profit
$\overline{w}_k, \overline{q}_{ik}$:	The equilibrium wholesale price and order quantity under no cost uncertainty
$w_k^{Z_1Z_2*}, q_{ik}^{Z_1Z_2*}$:	The equilibrium wholesale price and order quantity under subgame (Z_1, Z_2)

$\xi_{ki}^{Z_1Z_2}$, $f_{iki}^{Z_1Z_2}$: Response coefficients for supplier k and manufacturer i to c_{m_i} under subgame (Z_1, Z_2)
$\Pi_{s_k}^{Z_1Z_2*}$, $\Pi_{r_i}^{Z_1Z_2*}$: The optimal ex ante payoffs for supplier k and manufacturer i under subgame (Z_1, Z_2)
$\overline{\Pi}_{s_k}$, $\overline{\Pi}_{r_i}$: The optimal profit for supplier k and manufacturer i under no cost uncertainty.

Parameters

a: Demand intercept
c_{m_1}: Cost uncertainty for manufacturer i
σ_c^2: Variance of c_{m_i}
y_k: Yield uncertainty
μ, σ_y^2: Mean and variance of y_k
δ_y: The level of yield uncertainty $\delta_y = \sigma_y^2/\mu^2$
ρ: Correlated coefficient of suppliers' supply processes
η: Correlated coefficient of manufacturers' cost uncertainty
c: Supplier k's expected cost and $c = c_1/\mu + c_2$

Indices

Subscript

s_k: It captures supplier k
m_i: It captures manufacturer i

Superscript

Y: It indicates that the manufacturer agrees to VCIS
N: It indicates that the manufacturer does not agree to VCIS.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] H. L. Lee and S. Whang, "Information sharing in a supply chain," *International Journal of Manufacturing Technology and Management*, vol. 1, no. 1, pp. 79–93, 2000.

[2] L. Li and H. T. Zhang, "Confidentiality and information sharing in supply chain coordination," *Management Science*, vol. 54, no. 8, pp. 1467–1481, 2008.

[3] K. Zhu, "Information transparency of business-to-business electronic markets: a game-theoretic analysis," *Management Science*, vol. 50, no. 5, pp. 670–685, 2004.

[4] J. Recha, J. Kinyangi, and H. Omondi, "Climate related risks and opportunities for agricultural adaptation in semi-arid eastern Kenya," CCAFS East Africa Program Project Report, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark, 2013, http://hdl.handle.net/10568/24695.

[5] E. Y. Nyamah, Y. Jiang, Y. Feng, and E. Enchill, "Agri-food supply chain performance: an empirical impact of risk," *Management Decision*, vol. 55, no. 5, pp. 872–891, 2017.

[6] C. A. MacKenzie and A. Apte, "Modeling disruption in a fresh produce supply chain," *The International Journal of Logistics Management*, vol. 28, no. 2, pp. 656–679, 2017.

[7] M. de Keizer, R. Akkerman, M. Grunow, J. M. Bloemhof, R. Haijema, and J. G. van der Vorst, "Logistics network design for perishable products with heterogeneous quality decay," *European Journal of Operational Research*, vol. 262, no. 2, pp. 535–549, 2017.

[8] S. Jin, Y. Zhang, and Y. Xu, "Amount of information and the willingness of consumers to pay for food traceability in China," *Food Control*, vol. 77, pp. 163–170, 2017.

[9] F. Chen, "Information sharing and supply chain coordination," in *Handbooks in Operations Research and Management Science*, vol. 11, pp. 341–421, 2003.

[10] R. N. Clarke, "Collusion and the incentives for information sharing," *The Bell Journal of Economics*, vol. 14, no. 2, pp. 383–394, 1983.

[11] E. Galor, "Information sharing in oligopoly," *Econometrica*, vol. 53, no. 2, pp. 329–343, 1985.

[12] A. J. Kirby, "Trade associations as information exchange mechanisms," *The RAND Journal of Economics*, vol. 19, no. 1, pp. 138–146, 1988.

[13] X. Vives, "Duopoly information equilibrium: Cournot and Bertrand," *Journal of Economic Theory*, vol. 34, no. 1, pp. 71–94, 1984.

[14] L. Li, "Cournot oligopoly with information sharing," *The RAND Journal of Economics*, vol. 16, no. 4, pp. 521–536, 1985.

[15] Z. Z. Zhou and K. X. Zhu, "The effects of information transparency on suppliers, manufacturers, and consumers in online markets," *Marketing Science*, vol. 29, no. 6, pp. 1125–1137, 2010.

[16] J. H. Wu, X. Zhai, and Z. M. Huang, "Incentives for information sharing in duopoly with capacity constraints," *OMEGA - The International Journal of Management Science*, vol. 36, no. 6, pp. 963–975, 2008.

[17] K. Natarajan, D. Kostamis, and A. Merserean, "Strategic demand information sharing between competitors," Working Paper, University of North Carolina, Chapel Hill, NC, USA, 2013.

[18] L. Jiang and Z. Hao, "On the value of information sharing and cooperative price setting," *Operations Research Letters*, vol. 42, no. 6-7, pp. 399–403, 2014.

[19] L. Li, "Information sharing in a supply chain with horizontal competition," *Management Science*, vol. 48, no. 9, pp. 1196–1212, 2002.

[20] H. Zhang, "Vertical information exchange in a supply chain with duopoly retailers," *Production Engineering Research and Development*, vol. 11, no. 4, pp. 531–546, 2002.

[21] K. S. Anand and M. Goyal, "Strategic information management under leakage in a supply chain," *Management Science*, vol. 55, no. 3, pp. 438–452, 2009.

[22] G. Kong, S. Rajagopalan, and H. Zhang, "Revenue sharing and information leakage in a supply chain," *Management Science*, vol. 59, no. 3, pp. 556–572, 2013.

[23] N. Shamir, "Cartel formation through strategic information leakage in a distribution channel," *Marketing Science*, vol. 36, no. 1, pp. 70–88, 2017.

[24] A. Y. Ha, Q. Tian, and S. Tong, "Information sharing in competing supply chains with production cost reduction," *Manufacturing & Service Operations Management*, vol. 19, no. 2, pp. 246–262, 2017.
[25] A. Y. Ha, S. Tong, and H. Zhang, "Sharing demand information in competing supply chains with production diseconomies," *Management Science*, vol. 57, no. 3, pp. 566–581, 2011.
[26] G. D. Wu, Q. S. Kong, J. G. Shi, H. R. Karimi, and W. Zhang, "Information sharing and channel construction of supply chain under asymmetric demand information," *Journal of Applied Mathematics*, vol. 2014, Article ID 107589, 8 pages, 2014.
[27] L. Jiang and Z. Hao, "Incentive-driven information dissemination in two-tier supply chains," *Manufacturing and Service Operations Management*, vol. 18, no. 3, pp. 393–413, 2016.
[28] M. Zhou, B. Dan, S. Ma, and X. Zhang, "Supply chain coordination with information sharing: the informational advantage of GPOs," *European Journal of Operational Research*, vol. 256, no. 3, pp. 785–802, 2017.
[29] P. Zhang and Z. Xiong, "Information sharing in a closed-loop supply chain with asymmetric demand forecasts," *Mathematical Problems in Engineering*, vol. 2017, Article ID 9785759, 12 pages, 2017.
[30] D.-Q. Yao, X. H. Yue, and J. Liu, "Vertical cost information sharing in a supply chain with value-adding retailers," *Omega* , vol. 36, no. 5, pp. 838–851, 2008.
[31] H. Liu, S. Sun, M. Lei, G. K. Leong, and H. Deng, "Research on cost information sharing and channel choice in a dual-channel supply chain," *Mathematical Problems in Engineering*, vol. 2016, Article ID 4368326, 12 pages, 2016.
[32] D. Kostamis and I. Duenyas, "Purchasing under asymmetric demand and cost information: when is more private information better?" *Operations Research*, vol. 59, no. 4, pp. 914–928, 2011.
[33] G. P. Cachon and M. A. Lariviere, "Contracting to assure supply: how to share demand forecasts in a supply chain," *Management Science*, vol. 47, no. 5, pp. 629–646, 2001.
[34] C. Eksoz, S. A. Mansouri, and M. Bourlakis, "Collaborative forecasting in the food supply chain: a conceptual framework," *International Journal of Production Economics*, vol. 158, pp. 120–135, 2014.
[35] M. A. Resende-Filho and T. M. Hurley, "Information asymmetry and traceability incentives for food safety," *International Journal of Production Economics*, vol. 139, no. 2, pp. 596–603, 2012.
[36] C. A. Yano and H. L. Lee, "Lot sizing with random yields: a review," *Operations Research*, vol. 43, no. 2, pp. 311–334, 1995.
[37] Y.-J. Chen and C. S. Tang, "The economic value of market information for farmers in developing economies," *Production Engineering Research and Development*, vol. 24, no. 9, pp. 1441–1452, 2015.
[38] C. S. Tang, Y. Wang, and M. Zhao, "The implications of utilizing market information and adopting agricultural advice for farmers in developing economies," *Production Engineering Research and Development*, vol. 24, no. 8, pp. 1197–1215, 2015.
[39] S. Deo and C. J. Corbett, "Cournot competition under yield uncertainty: the case of the U.S. influenza vaccine market," *Manufacturing and Service Operations Management*, vol. 11, no. 4, pp. 563–576, 2009.
[40] S. Y. Tang and P. Kouvelis, "Supplier diversification strategies in the presence of yield uncertainty and buyer competition," *Manufacturing and Service Operations Management*, vol. 13, no. 4, pp. 439–451, 2011.

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Research Article

The Pricing Strategy of Oligopolistic Competition Food Firms with the Asymmetric Information and Scientific Uncertainty

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The arguments for and against genetically modified (GM) food focus on the characteristics of the scientific uncertainty and asymmetric information for the GM food. How do these two factors affect the competition and pricing strategy of food firms that separate GM food and conventional food conforming to consumer's right to know? We explore the issue of pricing strategies between two firms producing horizontally and vertically differentiated foods in the context of asymmetric information and scientific uncertainty. The theoretical results show that there are two separating perfect Bayesian equilibria in which the prices of the conventional food and GM food are strategic complements and the profits of two types of firms are both increasing in the price of GM food. The numerical example shows that a decrease of the expected potential net damage as the most sensitive parameter leads to an increase of the profits of the two firms. Additionally, an increase in product differentiation helps to increase the two firms' profits. Finally, the decrease in risk aversion as the second sensitive parameter helps to increase both products' prices and quantities and both firms' profits. This paper contributes by combining food safety regulation with market mechanisms and competition.

1. Introduction

How does asymmetric information and scientific uncertainty impact the pricing strategy of food firms and ultimately consumer understanding of the newer foods on the market? Food quality and safety are of great concern to governments, food enterprises, and, certainly, consumers [1, 2]. With the continuing development of economies, horizontally and vertically differentiated foods have been produced to meet consumers' needs regarding food quantity and variety [3]. However, because of the asymmetric information between consumers and food enterprises, consumers cannot identify the real quality until purchasing and consuming the experience goods, and they do not know the quality or variety even after consuming credence goods such as genetically modified (GM) food [4]. The application of transgenic technology can help to reduce food shortages and production costs [5], but GM food is also characterized by significant asymmetric information and scientific uncertainty, raising concerns for consumers and governments [6].

In order to satisfy the consumer's right to know, governments have taken measures with respect to food safety regulation [7, 8]. Apart from the government regulation to separate foods with differentiated qualities through labelling, the power of market mechanisms should not be ignored [9–11]. In this paper, we examine the effect of the asymmetric information and scientific uncertainty on the pricing strategies of food firms and try to combine the market mechanism with government regulation to separate GM food and conventional food, consistent with the consumer's right to know.

The competition among firms in the marketplace would be reflected in many ways, not just in price [12, 13]. A firm seeks to choose a combination of strategic variables such as price and product type (e.g., low or high; GM or conventional) that they expect would maximize profits [14–16]. However, some strategic variables are the firm's private information, which leads to information asymmetry between the firm and its consumers as well as between the firm and its rivals. The firm's choice of price may signal its type to consumers, for example.

In this article, we explore pricing strategies used by two firms that produce horizontally and vertically differentiated foods in the context of imperfect oligopolistic competition, incomplete information, and scientific uncertainty. We find that there are two separating perfect Bayesian equilibriums in which the price of the conventional food is significantly higher than that of GM food and the two prices are strategic complements.

There is a fairly extensive literature on the use price to signal product quality. From the perspective of a monopoly market structure, Bagwell and Riordan [17] examined a two-type model and showed that, compared to the price under full information, the low-quality firm charged the same price under incomplete information while the high-type firm charged a higher price in the context of asymmetric information. Daughety and Reinganum [18] extended the model developed by Bagwell and Riordan [17] by utilizing a continuum of types representing product safety. They showed that whether the higher price in fact signalled safer products depended on the allocation of the associated loss between the firm and the consumer and concluded that lower prices signalled safer products if the firm bore a sufficiently high percentage of the loss, while higher prices signal safer products if the consumer bore a sufficiently high percentage of the loss. Under monopolistic conditions, Mirman et al. [19] also studied the informational role of prices under the asymmetric information and noisy signalling.

For example, from the perspective of an oligopoly market structure, Janssen and Roy [20] developed a symmetric Bertrand oligopoly model and studied the competitive strategy between the high-quality and the low-quality firms. They found that there existed Bayesian separating equilibria in which the low-quality firms chose random pricing strategy and the high-quality firms charged high prices. Different from Janssen and Roy [20], Daher et al. [21] assumed that the quality was common knowledge to all the firms since firms sold a homogeneous good, but consumers owned incomplete information on product quality. They found the price under the (signalling) Cournot equilibrium was higher than that under the full-information Cournot equilibrium and the profits under a signalling Cournot were equal to the profits of a cartel with full information. Based on Janssen and Roy [20], Dubovik and Janssen [12] set up an oligopoly model where consumers had heterogeneous information. They showed that when there was a sufficiently high portion of uninformed consumers, there existed a unique equilibrium where high price was associated with high quality. However, this equilibrium was Pareto-inefficient since firms had incentives to distort quality downwards. Following Janssen and Roy [20], Adriani and Deidda [22] also assumed all firms produce the same good whose quality is known to all firms but unknown to uninformed buyers. Adriani and Deidda [22] explored the impact of the strength of competition among sellers on the ability of high-quality sellers to inform consumers about the quality of their goods through the pricing strategy when there were a large number of price-setting sellers and a large number of consumers. They showed that high-quality sellers could use price to signal their high quality in the context of weak competition among sellers. On the contrary, high-quality sellers failed to signal and then were driven out of the market if the competition among sellers were strong. Daughety and Reinganum [23] described the role of quality signalling via price and quality disclosure through a credible direct claim played in the market competition. In the context of sufficiently high disclosure costs, the firm would always use price to signal the quality of its product. In the unique separating equilibrium, consumers inferred the quality of the product through its price and then made their purchasing decisions. In contrast, if the disclosure costs were zero, then all types of firms would disclosure their qualities and charge the full-information prices according to their own types. In this situation, consumers made decisions according to prices and qualities of the products. Furthermore, Janssen and Roy [24] explained why it was hard for firms to voluntarily disclose quality in a symmetric duopoly. In the context of the relatively low-quality premiums, the unique symmetric equilibrium was to not disclose product quality (for both firms), even if the disclosure costs were zero. In the context of the relatively high-quality premium and the increasing cost in quality, there were two equilibriums: full disclosure and nondisclosure.

As such, our study differs from the previous studies in several ways. First, we construct a representative consumer's model in an oligopolistic market with the scientific uncertainty. Though GM food is generally considered as safe, there are still some unknowns compared to conventional food, particularly with respect to human health [25, 26]. We treat the scientific uncertainty as a kind of risk with a distribution that has known expected potential net damage and variance. Additionally, we consider the consumers' heterogeneous degree of risk aversion and study the effects of various degrees of risk aversion on the prices, quantities, and profits in the separating equilibrium. Finally, the products in our model are horizontally and vertically differentiated.

In addition, the paper's numerical simulation and sensitivity analysis both suggest important policy implications. First, the expected potential net damage is the most sensitive parameter regarding the price of GM food, the quantities of the conventional food and GM food, and the profits of the two types of firms, making government information particularly important for consumers. Although some recent studies show GM food may have potential damage to human health [26], many studies also show GM food is as safe as the conventional food [27]. Thus, due to the scientific uncertainty of GM food's impact on human health, the expectation of the potential risk is there, though it has gotten lower as more study is undertaken. Moreover, the two kinds of foods' price and quantities and two firms' profits increase as the product differentiation increases. Government has a role in encouraging the innovation of food to increase the product differentiation. Finally, the degree of risk aversion is very sensitive to the price of GM food and the profits of the firm producing the conventional food. Governments should consider the heterogeneity of consumers when developing policies.

The paper is organized as follows. The next section describes models of the representative consumer and two firms and Section 3 discusses the theoretical separating equilibrium. Section 4 further analyses the prices, quantities, and profits in the separating equilibrium using numerical examples. Additionally an extension is conducted to study how the changes in the parameters affect prices, quantities, and profits. The final section presents general conclusions from the results with policy recommendations.

2. Model Setup

Our theoretic model includes a representative consumer and two firms. The representative consumer has a certain degree of risk aversion on the potential damage from GM food. Each firm produces its product with constant marginal costs depending on the type of its product. Additionally, the products in our model are horizontally and vertically differentiated. Horizontal differentiation means there exists difference between two firms' products' qualities. Vertical differentiation means there are two versions including conventional food and GM food for each product. In our model, first, nature independently decides the types of the two firms from a common distribution and each firm can observe its own type. Second, two firms simultaneously choose product prices based on their own types, and finally the representative consumer determines quantities of the products based on the observed price. In the model with asymmetric information, one firm does not observe the type of food produced by the other firm, and the representative consumer does not observe the two firms' food types. In the model with full information, firms and consumers observe all the food types.

Based on backward induction, we firstly solve consumer's problem and then firms' problems.

2.1. Consumer's Problem. We consider a representative consumer with risk aversion, who consumes some of each product. Products 1 and 2 are differentiated goods and the two products are substitutes. The third is a numeraire good. Products 1 and 2 can be either conventional or GM food (signified by T or G, resp.).

Horizontal differentiation is captured by a consumer-specific incremental value of one kind of product. Some consumers are willing to pay P for one unit of Product 1 and $P + \varepsilon$ for one unit of Product 2 while, all else equal, another part of consumers are willing to pay P for one unit of Product 1 and $P - \varepsilon$ for one unit of Product 2. The consumer-specific incremental net value will be indicated by horizontal differentiation.

As for the vertical differentiation, the two products are vertically differentiated in regard to the quality. All consumers will prefer safer product to one with a lower level of safety. Any consumers prefer the product without scientific uncertainty to one with scientific uncertainty if both products are sold at the same price.

Assumption 1 ($(\theta_G, \theta_T) = (0, 1)$). θ_i denotes an indicator function which takes on 0 when product i is GM food and takes on 1 when product i is the conventional food. And hence $(\theta_G, \theta_T) = (0, 1)$.

The consumer chooses the food variety and quantity to maximize the utility. According to Daughety and Reinganum [23, 28] we set up an initial quadratic utility function. Considering the scientific uncertainty of GM food, we view the scientific uncertainty as a risk with a certain expectation and variation and deal with the risk by introducing the mean and variation into the initial quadratic utility function based on the method of Johnstone and Lindley [29]. The utility function is shown in the following assumption.

Assumption 2. The consumer's utility function is quadratic in the two differentiated products with the parameters $\alpha > 0$, $\beta > \gamma > 0$, $\tau > 0$, and $\delta \sim N(E(\delta), \mathrm{var}(\delta))$.

$$U(q_1, q_2) = \sum_{i=1}^{2} q_i \left[\alpha - (1-\theta_i) E(\delta)\right] - \frac{1}{2}\left(\sum_{i=1}^{2} \beta q_i^2 + \sum_{i}\sum_{j \neq i} \gamma q_i q_j\right) - \frac{1}{2}\sum_{i=1}^{2}\left[\tau (1-\theta_i)^2 \mathrm{var}(\delta)\right] q_i^2, \tag{1}$$

where γ is the degree of product substitution between the two goods produced by Firms 1 and 2.

As γ decreases, the two kinds of products are more differentiated and consumer's utility goes up. We assume that γ lies in the interval $(0, \beta)$. The coefficient α means the basic utility of consuming one unit of the conventional food. The parameter $\delta \sim N(E(\delta), \mathrm{var}(\delta))$ means scientific uncertainty from GM food. GM food may or may not be as safe as the conventional food to human health. Meanwhile, genetic modification necessarily improves some traits of plants such as resistance to pests and tolerance to bad conditions. $E(\delta)$ means the expected potential damage minus the utility increase from the improved traits and $\mathrm{var}(\delta)$ is the volatility of risk. τ is the degree of risk aversion. A consumer's utility of consuming one unit of GM food goes down as τ increases.

The consumer chooses quantities (q_1 and q_2) to maximize his/her utility with income I; that is, $\max_{q_1, q_2} U(q_1, q_2) + I - \sum_{i=1}^{2} p_i q_i$, where $I - \sum_{i=1}^{2} p_i q_i$ means the consumption of the numeraire good.

First-order conditions show the inverse demand function for product i is

$$p_i(q_i, q_{-i}) = \alpha - (1-\theta_i) E(\delta) - \left[\beta + \tau (1-\theta_i)^2 \mathrm{var}(\delta)\right] q_i - \gamma q_{-i}. \tag{2}$$

Obviously $p_i < \alpha$ always holds.

Since we focus on firms' pricing strategy to signal their product quality, here we further need the following ordinary demand function:

$$q_i(p_i, p_{-i}) = \frac{[\alpha - (1-\theta_i)E(\delta)]\left[\beta + \tau(1-\theta_{-i})^2 \operatorname{var}(\delta)\right] - \gamma[\alpha - (1-\theta_{-i})E(\delta)]}{\left[\beta + \tau(1-\theta_i)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau(1-\theta_{-i})^2 \operatorname{var}(\delta)\right] - \gamma^2} + \frac{\gamma p_{-i} - \left[\beta + \tau(1-\theta_{-i})^2 \operatorname{var}(\delta)\right] p_i}{\left[\beta + \tau(1-\theta_i)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau(1-\theta_{-i})^2 \operatorname{var}(\delta)\right] - \gamma^2}. \tag{3}$$

The equation above represents the consumer's demand in the context of full information. However, when information asymmetry exists, the representative consumer could not observe products' qualities but only have perceptions of products' qualities, denoted by $\widetilde{\theta}_i$, $(i = 1, 2)$. And hence substituting $\widetilde{\theta}_i$ for θ_i of the above equation yields demand functions under the condition of asymmetric information.

2.2. The Firm's Problem. It is known that the application of transgenic technology can reduce agricultural production costs [5, 30]. For simplicity, we assume the marginal cost of GM food is normalized to zero and that of conventional food is $k > 0$. Additionally, we maintain the following assumption throughout this paper.

Assumption 3 ($E(\delta_i) > k > 0$). $E(\delta_i) > k$ means the consumer would be willing to pay k to buy the conventional food to avoid the expected loss $E(\delta_i)$ from purchasing and consuming one unit of GM food.

Given the rival's price and perceived product type, one firm's profits can be expressed as a function of its price, cost, true product type, and perceived product type. In the context of full information, the perceived type is consistent with the true product type. However, under the condition of asymmetric information, the perceived type may be different from the true product type. And hence firm i's profits can be written as

$$\pi_i(p_i, \theta_i, \widetilde{\theta}_i \mid p_{-i}, \widetilde{\theta}_{-i}) = (p_i - k\theta_i)\left\{\frac{[\alpha - (1-\widetilde{\theta}_i)E(\delta)]\left[\beta + \tau(1-\widetilde{\theta}_{-i})^2 \operatorname{var}(\delta)\right] - \gamma[\alpha - (1-\widetilde{\theta}_{-i})E(\delta)]}{\left[\beta + \tau(1-\widetilde{\theta}_i)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau(1-\widetilde{\theta}_{-i})^2 \operatorname{var}(\delta)\right] - \gamma^2} + \frac{\gamma p_{-i} - \left[\beta + \tau(1-\widetilde{\theta}_{-i})^2 \operatorname{var}(\delta)\right] p_i}{\left[\beta + \tau(1-\widetilde{\theta}_i)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau(1-\widetilde{\theta}_{-i})^2 \operatorname{var}(\delta)\right] - \gamma^2}\right\}. \tag{4}$$

A firm has the full information about its own marginal cost and hence we do not use $k\widetilde{\theta}_i$ but $k\theta_i$ to mean firm i' marginal cost in its profits function. The second term above is the consumer's demand based on the prices and his perceived types of two firms' products.

For the game with asymmetric information, we characterize a symmetric separating perfect Bayesian equilibrium. Firm i does not know the product type of its rival and predicts that its rival uses the pricing strategy $p^*(\theta)$ by charging the price $p^*(1)$ with probability λ and the price $p^*(0)$ with probability $1 - \lambda$. Thus, firm i's expected profits with respect to θ_{-i} can be written as

$$E_{-i}\left[\pi_i(p_i, \theta_i, \widetilde{\theta}_i \mid p_{-i}, \widetilde{\theta}_{-i})\right] = (p_i - k\theta_i)E_{-i}\left\{\frac{[\alpha - (1-\widetilde{\theta}_i)E(\delta)]\left[\beta + \tau(1-\widetilde{\theta}_{-i})^2 \operatorname{var}(\delta)\right] - \gamma[\alpha - (1-\widetilde{\theta}_{-i})E(\delta)]}{\left[\beta + \tau(1-\widetilde{\theta}_i)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau(1-\widetilde{\theta}_{-i})^2 \operatorname{var}(\delta)\right] - \gamma^2} + \frac{\gamma p_{-i} - \left[\beta + \tau(1-\widetilde{\theta}_{-i})^2 \operatorname{var}(\delta)\right] p_i}{\left[\beta + \tau(1-\widetilde{\theta}_i)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau(1-\widetilde{\theta}_{-i})^2 \operatorname{var}(\delta)\right] - \gamma^2}\right\}. \tag{5}$$

Simplifying the second term yields firm i's expected profits:

$$\Pi_i\left(p_i,\theta_i,\widetilde{\theta}_i \mid E\left(p^*\right)\right)=\left(p_i-k\theta_i\right)\left\{\frac{\left[\alpha-\left(1-\widetilde{\theta}_i\right)E\left(\delta\right)\right]\left[\beta+\tau\left(1-\lambda\right)^2\operatorname{var}\left(\delta\right)\right]-\gamma\left[\alpha-\left(1-\lambda\right)E\left(\delta\right)\right]}{\left[\beta+\tau\left(1-\widetilde{\theta}_i\right)^2\operatorname{var}\left(\delta\right)\right]\left[\beta+\tau\left(1-\lambda\right)^2\operatorname{var}\left(\delta\right)\right]-\gamma^2}\right.$$
$$\left.+\frac{\gamma E\left(p^*\right)-\left[\beta+\tau\left(1-\lambda\right)^2\operatorname{var}\left(\delta\right)\right]p_i}{\left[\beta+\tau\left(1-\widetilde{\theta}_i\right)^2\operatorname{var}\left(\delta\right)\right]\left[\beta+\tau\left(1-\lambda\right)^2\operatorname{var}\left(\delta\right)\right]-\gamma^2}\right\}, \tag{6}$$

where $E(p^*)=\lambda p^*(1)+(1-\lambda)p^*(0)$.

Moreover, the second term above is linear in the rival's price but nonlinear in the rival's product types. Irrespective of true product type, it is always more profitable to be perceived as type T when prices are given since $\partial\Pi_i(p_i,\theta_i,\widetilde{\theta}_i \mid E(p^*))/\partial\widetilde{\theta}_i>0$ always holds. Let $B(p)$ denote the consumer's belief function. The consumer infers firm i to be of type $B(p_i)$ based only on the price p_i charged by firm i. When the representative consumer's belief function and the rival's pricing strategy are given, two firms manage to maximize their own expected profits in equilibrium. Specifically, the separating perfect Bayesian equilibrium would be formalized as follows.

Definition 4. The separating perfect Bayesian equilibrium consists of a pair of prices $(p^*(0),p^*(1))=(P_G,P_T)$ and beliefs $B^*(p)$ such that, for $i=1,2$,

(i) $\Pi_i(P_G,0,0 \mid E(p^*))\ge \max_p\Pi_i(p,0,B^*(p) \mid E(p^*))$,

(ii) $\Pi_i(P_T,1,1 \mid E(p^*))\ge \max_p\Pi_i(p,1,B^*(p) \mid E(p^*))$.

Parts (i) and (ii) show that the consumer's beliefs are consistent with the fact in equilibrium. When one firm charges P_G, the consumer believes the firm produces GM food. When one firm charges P_T, the consumer believes the firm produces conventional food. Moreover, in the context of the given pricing strategy of the rival and the consumer's belief function, part (i) says the firm producing GM food prefers to charge P_G, while part (ii) says the firm producing conventional food prefers to charge P_T in the separating perfect Bayesian equilibrium.

3. Theoretical Analyses

In this section, we solve for a separating perfect Bayesian equilibrium; that is, we solve for the pricing strategy (P_G,P_T), the associated quantities (Q_G,Q_T), and the associated profits (Π_G,Π_T).

Each firm has full information on his own product type and cost, and let $c_u=k\theta_u$, where $u=G,T$. Based on Assumption 1 $(\theta_G=0,\theta_T=1)$, we have $(c_G,c_T)=(0,k)$ which is consistent with the previous assumption on marginal costs.

The firm's demand based on its perceived product type is $(d_v-p)h_v$, where $v=G,T$, $d_v\equiv[\alpha-(1-\widetilde{\theta}_v)E(\delta)]-e\gamma[\alpha-(1-\lambda)E(\delta)-E(p^*)]$, $h_v\equiv f_v/e$, $e\equiv 1/(\beta+\tau(1-\lambda)^2\operatorname{var}(\delta))$, and $f_v\equiv 1/([\beta+\tau(1-\widetilde{\theta}_v)^2\operatorname{var}(\delta)][\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)]-\gamma^2)$. And hence the firm's profits can be rewritten as $\Pi_{uv}=(p-c_u)h_v(d_v-p)$, where the true type $u=G,T$ and the perceived type $v=G,T$.

To guarantee that a firm always has positive profits, regardless of the perceived product type and the rival firm's pricing strategy, we need $d_v>c_u$ for all u, v. Its tightest constraint is $\min(d_v)>\max(c_u)$; that is,

$$\alpha-\left(1-\widetilde{\theta}_i\right)E\left(\delta\right)-e\gamma\left[\alpha-\left(1-\lambda\right)E\left(\delta\right)-E\left(p^*\right)\right]=d_G>c_T=k. \tag{7}$$

Considering that λ may be arbitrarily close to 1, $E(p^*)$ may be arbitrarily close to 0, and k (though smaller) may be arbitrarily close to $E(\delta)$, we employ the following sufficient condition.

Assumption 5 ($\alpha>2E(\delta)\beta/(\beta-\gamma)$). Notice that Assumption 5 is a strong sufficient condition for $d_G>c_T$, not a necessary condition. Obviously d_G is not less than $\alpha(1-\gamma/\beta)-E(\delta)$ and Assumption 5 yields $\alpha(1-\gamma/\beta)-E(\delta)>E(\delta)$. And hence $d_G>E(\delta)$. Based on the fact $c_T=k$ and Assumption 3, we obtain $d_G>c_T$.

Proposition 6. *The prices $p_{uv}=(c_u+d_v)/2$ to maximize one firm's profits given pricing strategy of the rival are ordered as follows: $p_{TT}>p_{GT}>p_{TG}>p_{GG}$, where u means the true product type and v means the perceived product type, and $u=G,T$, $v=G,T$.*

Obviously, profits Π_{uv} would be maximized when $p_{uv}=(c_u+d_v)/2$. Since the production cost is an increasing function of the true type of products and d_v is an increasing function of the perceived product type, the price p_{GT} or p_{TG} will fall in between p_{TT} and p_{GG}.

According to the fact $E(\delta_i)=d_T-d_G$ and Assumption 3, we can obtain that p_{GT} is higher than p_{TG}. The price charged by the T-type firm which is perceived as the G-type firm is higher than the price charged by the G-type firm which is perceived as the T-type firm if the consumer is willing to pay k to buy the conventional food to avoid the expected loss from GM food. The incorrect perception of consumers will negatively affect the production enthusiasm of the T-type firm. It reflects the importance of consumer's perception and the exact quality signalling by price.

Lemma 7. *Given $E(p^*)$, in the separating equilibrium, T-type firm's best response is $p_T(E(p^*)) = 0.5(d_T + \sqrt{d_T^2 - (h_G/h_T)d_G^2})$, while G-type firm's best response is $p_G(E(p^*)) = d_G/2$. Additionally, the own-price and the expected rival's price are strategic complements.*

As introduced before, we have the maximum profits $\max(\Pi_{uv}) = h_v(d_v - c_u)^2/4$. If a firm of type G is perceived as being of type G, its best response is p_{GG}. If the T-type firm is perceived as such, its best response is p_{TT}. However, we need to judge whether p_{TT} meets the need of the separating perfect Bayesian equilibrium.

The proof of Lemma 7 is presented in Appendix.

According to Lemma 7, we know two firms' best responses $p_T(E(p^*))$ and $p_G(E(p^*))$ are both the function of $E(p^*)$ since both d_T and d_G contain the term of $E(p^*)$. After we derive the solution to $E(p^*)$, we can obtain the best responses of the two types.

We can see that the pricing strategy between the G-type firm and the T-type firm are complementary. In the situation of information asymmetry, the behavior of the T-type firm will be affected by the pricing strategy of the G-type firm. The consistent pricing strategy is advantageous to itself and its opponent. In the face of raising price of GM food, the T-type firm will be afraid that its conventional food may be viewed as GM food if it does not put up the price of the conventional food.

Proposition 8. *There are two separating perfect Bayesian equilibriums consisting of a pair of prices (P_G, P_T) with $P_G < P_T$, and supporting beliefs $B(p^*)$, with $B(p^*) = 1$ when $p \geq P_T$, and $B(p^*) = 0$ when $p < P_T$.*

The proof of Proposition 6 is presented in Appendix.

In both Bayesian equilibriums, the price is a good signal of the type of foods. The food with the higher price of P_T is perceived as the conventional food. Otherwise, the food would be viewed as GM food. The price of conventional food is significantly higher than that of GM food in terms of separating equilibrium, and additionally the price gap between the conventional food and GM food is positively correlated to the expected net potential damage $E(\delta)$ because of the positive correlation between ω^* and $E(\delta)$.

Proposition 9. *In the separating perfect Bayesian equilibrium, $Q_T < Q_G$ holds if $(p_T - p_G - E(\delta))/p_G > 1 - h_G/h_T$; $Q_T > Q_G$ holds if $(p_T - p_G - E(\delta))/p_G < 1 - h_G/h_T$, where $h_G = (\beta + \tau(1-\lambda)^2\mathrm{var}(\delta))/([\beta + \tau\mathrm{var}(\delta)][\beta + \tau(1-\lambda)^2\mathrm{var}(\delta)] - \gamma^2)$ and $h_T = (\beta + \tau(1-\lambda)^2\mathrm{var}(\delta))/(\beta[\beta + \tau(1-\lambda)^2\mathrm{var}(\delta)] - \gamma^2)$.*

In the separating perfect Bayesian equilibrium, two firms' quantities are $Q_G = h_G Y^*$ and $Q_T = h_T(d_T - p_T) = h_T(Y^* + E(\delta)/2 - \omega^*)$, respectively. We know the equilibrium prices of GM food and conventional food are $p_G = Y^*$ and $p_T = Y^* + \omega^* + E(\delta)/2$, respectively. It means that, in the separating perfect Bayesian equilibrium, the demand of the conventional food is smaller than that of GM food if the expected net potential damage of GM food is small enough or the gap between the price of conventional food and GM food is big enough; otherwise the demand of GM food is smaller than that of the conventional food.

This reflects the distortion in prices due to signalling product type when the expected net potential damage of GM food is small enough or the gap between the prices of conventional food and GM food is big enough. In this situation, the price from the T-type firm is so much higher than the price charged by the G-type firm that it is not worth avoiding the risk from the scientific uncertainty by paying a high price for the convention food and that consumers are redistributed toward the G-type firm.

Proposition 10. *The profits of the G-type firm and the T-type firm are both monotonically increasing in the price of GM food.*

It can be proved that the profit of the G-type firm is increasing with the price of the GM food. In addition, we can also get that, with the increase of GM food price, the profits of T-type firm will rise since the pricing strategy between the G-type firm and the T-type firm is complementary.

In the situation of information asymmetry, the optimal pricing strategy of the T-type firm will be affected by the behavior of the G-type firm. The consistent pricing strategy is beneficial to itself and its opponent. When the G-type firm enhances the price of GM food, the optimal strategy for the T-type firm is to put up the price of the conventional food in case the conventional food is viewed as GM food and further enlarges its profit.

Proposition 11. *The separating perfect Bayesian equilibrium consisting of a pair of larger prices (P_G^*, P_T^*) is the first-best solution if $P_G^* < P_T^* < \alpha$; smaller prices (P_G^*, P_T^*) are the first-best solution if $P_T^* \geq P_G^* \geq \alpha$.*

Although (A.8) in the part of proof of Proposition 8 has two positive roots, which one is the optimal solution? The answer depends on the profits and the basic utility α. Proposition 10 shows the profits functions of the G-type firm and the T-type firm both monotonically increase as the price of GM food. Therefore, in terms of the principle of maximizing profits, the bigger Y^* is the more optimal the solution is.

In this equilibrium, P_T^* is the lowest price that the T-type firm can distinguish from a G-type firm and receive the maximum profit. The higher price than P_T^* also signals the conventional food but is less profitable for the T-type firm. On the contrary, the lower price than P_T^* charged by the T-type firm will provide a profitable deviation for a G-type firm if consumers infer that the G-type firm charging that price is a T-type firm.

In short, the separating perfect Bayesian equilibrium consisting of the higher price combination is the first-best solution when the price of the conventional food is low enough (i.e., lower than the basic utility α). In contrast, the lower price combination is the optimal solution when the price of GM food is high enough (i.e., higher than the basic utility α).

4. Numerical Simulation

In this section, we further analyze the separating perfect Bayesian equilibrium under the asymmetric information using numerical examples. Based on Assumptions 1–5, consider $\alpha = 10$; $\beta = 2$; $\gamma = 0.5$; $\tau = 0.5$; $\lambda = 0.5$; $k = 2.5$; $E(\delta) = 3$; $\mathrm{var}(\delta) = 1.5$.

We begin by solving for (q_1, q_2). To do so we solve $\max_{q_1,q_2} U(q_1, q_2) + I - \sum_{i=1}^{2} p_i q_i$ and obtain the following ordinary demand function:

$$q_i(p_i, p_{-i}) = \frac{[10 - 3(1-\theta_i)]\left[2 + 0.5(1-\theta_{-i})^2 \times 1.5\right] - 0.5[\alpha - (1-\theta_{-i})E(\delta)] + \gamma p_{-i} - \left[2 + 0.5(1-\theta_{-i})^2 \times 1.5\right] p_i}{\left[2 + 0.5(1-\theta_i)^2 \times 1.5\right]\left[2 + 0.5(1-\theta_{-i})^2 \times 1.5\right] - 0.5^2}. \quad (8)$$

And hence firm i's profits are as follows:

$$\begin{aligned}\pi_i\left(p_i, \theta_i, \tilde{\theta}_{-i} \mid p_{-i}, \tilde{\theta}_{-i}\right) = (p_i - 2.5\theta_i)&\left\{\frac{\left[10 - 3\left(1-\tilde{\theta}_i\right)\right]\left[2 + 0.5\left(1-\tilde{\theta}_{-i}\right)^2 \times 1.5\right] - 0.5\left[10 - 3\left(1-\tilde{\theta}_{-i}\right)\right]}{\left[2 + 0.5\left(1-\tilde{\theta}_i\right)^2 \times 1.5\right]\left[2 + 0.5\left(1-\tilde{\theta}_{-i}\right)^2 \times 1.5\right] - 0.5^2}\right. \\ &+ \left.\frac{0.5p_{-i} - \left[2 + 0.5\left(1-\tilde{\theta}_{-i}\right)^2 \times 1.5\right] p_i}{\left[2 + 0.5\left(1-\tilde{\theta}_{-i}\right)^2 \times 1.5\right]\left[2 + 0.5\left(1-\tilde{\theta}_{-i}\right)^2 \times 1.5\right] - 0.5^2}\right\},\end{aligned} \quad (9)$$

and firm i's expected profits are

$$\begin{aligned}\Pi_i\left(p_i, \theta_i, \tilde{\theta}_i \mid E(p^*)\right) = (p_i - 2.5\theta_i)&\left\{\frac{\left[10 - 3\left(1-\tilde{\theta}_i\right)\right]\left[2 + 0.5(1-\lambda)^2 \times 1.5\right] - 0.5[10 - 3(1-\lambda)]}{\left[2 + 0.5\left(1-\tilde{\theta}_i\right)^2 \times 1.5\right]\left[2 + 0.5(1-\lambda)^2 \times 1.5\right] - 0.5^2}\right. \\ &+ \left.\frac{0.5E(p^*) - \left[2 + 0.5(1-\lambda)^2 \times 1.5\right] p_i}{\left[2 + 0.5\left(1-\tilde{\theta}_i\right)^2 \times 1.5\right]\left[2 + 0.5(1-\lambda)^2 \times 1.5\right] - 0.5^2}\right\},\end{aligned} \quad (10)$$

where $E(p^*) = 0.5p^*(1) + 0.5p^*(0)$.

Thus, based on Proposition 10, in the separating perfect Bayesian equilibrium, the prices of GM food and conventional food are $p_G = 1.53$ and $p_T = 5.77$, respectively. The corresponding quantities are $Q_G = 0.58$ and, $Q_T = 0.15$, respectively. $Q_T < Q_G$ since $(\omega^* - 0.5E(\delta))/Y^* > 1 - h_G/h_T$ holds in this example. Two firms' profits are $\Pi_T = 0.89$ and $\Pi_G = 0.50$, respectively.

In this section, we will investigate how the change in the model parameters affect the pricing strategy (P_G, P_T), the associated quantities (Q_G, Q_T), and the associated profits (Π_G, Π_T) in the separating perfect Bayesian equilibrium. We focus on the following four categories of parameters: (i) parameters on the scientific uncertainty: $E(\delta)$ and $\mathrm{var}(\delta)$; (ii) parameters on the asymmetric information: λ; (iii) parameters on the degree of product substitution γ; (iv) parameters on the degree of risk aversion τ.

Table 1 illustrates the effects of changing four categories of parameters on the price of GM food P_G. It shows that increases of the expected net potential damage $E(\delta)$, the perceived proportion of T-type firm λ, the degree of product substitution γ, and the degree of risk aversion τ all lead to decreases of the price of GM food; an increase of the volatility of potential risk $\mathrm{var}(\delta)$ leads to an increase of the price of GM food. From the perspective of the average volatility, P_G is more sensitive to the expected net potential damage $E(\delta)$ compared to another four parameters.

Table 2 reveals the effects of changing four categories of parameters on the price of the conventional food P_T. From Table 2 we can see that increases of the expected net potential damage $E(\delta)$ and the volatility of potential risk $\mathrm{var}(\delta)$ both lead to increases of the price of the conventional food; increases of the perceived proportion of T-type firm λ,

Table 1: Effects of changing four categories of parameters on P_G.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	1.6773	1.6405	1.6036	1.5668	1.5299	1.4930	1.4561	1.4192	1.3823
$\mathrm{var}(\delta)$	1.5267	1.5275	1.5283	1.5291	1.5299	1.5307	1.5315	1.5323	1.5331
γ	1.5695	1.5594	1.5494	1.5395	1.5299	1.5205	1.5114	1.5024	1.4938
τ	1.5828	1.5641	1.5498	1.5387	1.5299	1.5230	1.5175	1.5130	1.5095
λ	1.5484	1.5439	1.5393	1.5346	1.5299	1.5252	1.5204	1.5156	1.5107

Table 2: Effects of changing four categories of parameters on P_T.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	5.3805	5.4796	5.5774	5.6741	5.7696	5.8641	5.9576	6.0502	6.1419
$\mathrm{var}(\delta)$	5.7457	5.7519	5.7580	5.7639	5.7696	5.7752	5.7807	5.7861	5.7914
γ	5.8352	5.8183	5.8018	5.7855	5.7696	5.7541	5.7390	5.7243	5.7102
τ	5.8402	5.8138	5.7944	5.7801	5.7696	5.7620	5.7566	5.7529	5.7507
λ	5.8009	5.7932	5.7855	5.7776	5.7696	5.7616	5.7534	5.7452	5.7370

Table 3: Effects of changing four categories of parameters on Q_G.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	0.6364	0.6224	0.6084	0.5944	0.5805	0.5665	0.5525	0.5385	0.5244
$\mathrm{var}(\delta)$	0.6147	0.6057	0.5971	0.5886	0.5805	0.5725	0.5648	0.5573	0.5500
γ	0.5863	0.5846	0.5830	0.5817	0.5805	0.5795	0.5787	0.5781	0.5778
τ	0.6373	0.6203	0.6055	0.5923	0.5805	0.5696	0.5596	0.5503	0.5415
λ	0.5865	0.5851	0.5836	0.5820	0.5805	0.5789	0.5773	0.5756	0.5740

the degree of product substitution γ, and the degree of risk aversion τ all lead to decrease of the price of the conventional food. Moreover, P_G is more sensitive to the expected net potential damage $E(\delta)$ compared to the volatility of potential risk $\mathrm{var}(\delta)$, the degree of product substitution γ, the perceived proportion of T-type firm λ, and the degree of risk aversion τ.

Tables 3–6 show the effects of changing four categories of parameters on the quantity of GM food, the quantity of the conventional food, the profits of G-type firm, and the profits of T-type firm. We see that the quantity of GM food, the quantity of the conventional food, the profits of G-type firm, and the profits of T-type firm all decrease as the expected net potential damage $E(\delta)$, and the volatility of potential risk $\mathrm{var}(\delta)$, the perceived proportion of T-type firm λ, the degree of product substitution γ, or the degree of risk aversion τ increases. Moreover, the quantity of GM food Q_G, the quantity of the conventional food Q_T, and the profits of G-type firm Π_G and T-type firm Π_T are all most sensitive to the expected net potential damage $E(\delta)$. It is essential to officially enhance the popularization of science on GM food to get the consumers' expected potential net damage stable or even lower. Finally, the degree of risk aversion τ is the second sensitive parameter to the profits of T-type firm Π_T. It should be noted that governments should not overlook the heterogeneity of consumers in their degree of risk aversion when making policy-decisions.

5. Conclusion

In this article, we combine the consumer's utility maximization model and the firm's profits maximization model. In doing so, we constructed a representative consumer's model in an oligopolistic market with information asymmetry and scientific uncertainty and horizontally and vertically differentiated and substitute goods. This paper treats the scientific uncertainty as a risk with a known distribution, the expected potential net damage, and the volatility of risk. We employ a signalling model in which the type of a firm's product is not public information, but private information; the firm's choice of price may signal its product type to consumers. In the separating perfect Bayesian equilibrium, there exists the lowest price for the T-type firm to distinguish itself from the G-type firm and maximize profits.

Deriving from these two models, we have been able to generate a variety of results. First, to maximize one firm's profits given pricing strategy of the rival, the firm charges the highest price if the T-type firm is perceived as such; the firm charges the second highest price if the G-type firm is perceived as the T-type firm; the firm charges the

Table 4: Effects of changing four categories of parameters on Q_T.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	0.1984	0.1863	0.1749	0.1641	0.1539	0.1442	0.1350	0.1263	0.1180
$\mathrm{var}(\delta)$	0.1633	0.1609	0.1585	0.1562	0.1539	0.1517	0.1496	0.1476	0.1456
γ	0.1577	0.1567	0.1557	0.1548	0.1539	0.1531	0.1524	0.1517	0.1512
τ	0.1727	0.1669	0.1619	0.1577	0.1539	0.1506	0.1475	0.1447	0.1421
λ	0.1566	0.1559	0.1553	0.1546	0.1539	0.1532	0.1525	0.1518	0.1511

Table 5: Effects of changing four categories of parameters on Π_G.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	1.0674	1.0210	0.9757	0.9314	0.8881	0.8458	0.8045	0.7642	0.7249
$\mathrm{var}(\delta)$	0.9384	0.9253	0.9125	0.9001	0.8881	0.8764	0.8650	0.8539	0.8431
γ	0.9203	0.9116	0.9033	0.8955	0.8881	0.8811	0.8746	0.8686	0.8631
τ	1.0087	0.9701	0.9383	0.9114	0.8881	0.8675	0.8492	0.8326	0.8174
λ	0.9082	0.9033	0.8983	0.8932	0.8881	0.8829	0.8777	0.8724	0.8671

Table 6: Effects of changing four categories of parameters on Π_T.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	0.5714	0.5552	0.5384	0.5210	0.5033	0.4852	0.4669	0.4484	0.4298
$\mathrm{var}(\delta)$	0.5301	0.5231	0.5163	0.5097	0.5033	0.4970	0.4909	0.4850	0.4792
γ	0.5260	0.5199	0.5141	0.5085	0.5033	0.4983	0.4936	0.4892	0.4852
τ	0.5769	0.5530	0.5335	0.5172	0.5033	0.4911	0.4804	0.4708	0.4620
λ	0.5168	0.5135	0.5101	0.5067	0.5033	0.4998	0.4963	0.4928	0.4892

second lowest price if the T-type firm is perceived as the G-type firm; the firm charges the lowest price if the G-type firm is perceived as such. The interesting result is the price charged by the T-type firm which is perceived as the G-type firm is higher than the price charged by the G-type firm which is perceived as the T-type firm, if the consumer is willing to pay k to buy the conventional food to avoid the expected loss from GM food. Second, there are two separating perfect Bayesian equilibriums in which the price of the conventional food is significantly higher than that of GM food and the own-price and the expected rival's price are strategic complements, and additionally the price gap between the conventional food and GM food enlarges as the expected net potential damage increases. The separating perfect Bayesian equilibrium consisting of the higher price combination is the first-best solution when the price of the conventional food is low enough (i.e., lower than the basic utility α). In contrast, the lower price combination is the optimal solution when the price of GM food is high enough (i.e., higher than the basic utility α). Actually, the price of GM food is larger than the basic utility when the difference between the conventional food and GM food is large enough. In the separating perfect Bayesian equilibriums, there exists the corresponding lowest price for the firm producing the conventional food to distinguish it from the other types of firms. Third, in the separating perfect Bayesian equilibrium, it is ambiguous whether the quantity of the conventional food is smaller than the quantity of GM food. Finally, the profits of the G-type firm and the T-type firm are both monotonically increasing in the price of GM food.

Our numerical example and sensitivity analysis also show that increases of the expected net potential damage, the perceived proportion of T-type firm, the degree of product substitution, and the degree of risk aversion all lead to decreases of the price of GM food; and an increase of the volatility of potential risk leads to an increase of the price of GM food. From the perspective of the average volatility, the price of GM food is most sensitive to the expected net potential damage.

Additionally, increases of the expected net potential damage and the volatility of potential risk both lead to increases of the price of the conventional food; increases of the perceived proportion of T-type firm, the degree of product substitution, and the degree of risk aversion all lead to decreases of the price of the conventional food. Moreover, the price of the conventional food is most sensitive to the expected net potential damage.

Finally, the quantity of GM food, the quantity of the conventional food, the profits of G-type firm, and the profits of T-type firm all decrease as the expected net potential damage, and the volatility of potential risk, the perceived proportion of T-type firm, the degree of product substitution, or the degree of risk aversion increases. Moreover, the quantities of GM food and the conventional food and the profits of G-type firm and T-type firm are all most sensitive to the expected net potential damage. Finally, the degree of risk aversion is the second sensitive parameter to the profits of T-type firm.

Several important policy implications emerge based on the results from our theory deduction and sensitivity analysis. First, the improved traits via genetically modified technology should be encouraged to be developed and presented to decrease the expected potential net damage and hence to increase the profits of both types of firms. Second, our simulation results show that the expected potential net damage is the most sensitive parameter to the prices of GM food and the conventional food, the quantities of the conventional food and GM food, and also the profits of two types of firms. Thus, government should help consumers to know more about GM food, particularly its generally regarded as safe nature. Although some recent studies show certain GM foods may negatively impact human health [26], numerous studies also show GM food to be as safe as the conventional food [27]. Labelling is not required for GM plant food since the Food & Drug Administration (FDA) in United States thinks GM food is bioequivalent to conventional plant food. The risk rankings of Costa-Font et al. [31] also indicate that GM food is perceived as less risky than irradiation, artificial growth hormones in food, or pesticides used in the production process. Thus, given these potential upsides, it is essential to officially enhance the popularization of the science on GM food to help reduce the consumers' expected potential fears. Third, governments should encourage the innovation of food products to increase the product differentiation, which helps increase the food's price, quantities, and firm profitability. Finally, our results show that the profit of the firm producing the conventional food is very sensitive to the degree of risk aversion, while the decrease in the degree of risk aversion helps increase the food's price, quantity, and the firm's profits. Different consumers have different degrees of risk aversion [32]. Government should consider the heterogeneity of consumers in their degree of risk aversion when making policy-decisions, particularly with wide-ranging public health concerns.

Appendix

Proof of Lemma 7. Based on Definition 4, in order to separate from G-type firm, the best response for the type T firm would be a member of the following set:

$$\left\{ p \mid (p - c_G) h_T (d_T - p) \le \frac{h_G (d_G - c_G)^2}{4},\ (p - c_T) h_T (d_T - p) \ge \frac{h_G (d_G - c_T)^2}{4} \right\}, \tag{A.1}$$

where $c_G = 0$ and $c_T = k$.

The first inequality says that G-type firm prefers to charge price p_{GG} rather than price p to be perceived as T-type, which means G-type firm has no incentive to act as T-type in this situation. The second inequality says that T-type firm prefers to charge price p to be perceived as T-type rather than p_{TG}, which means it is worthwhile for the T-type firm to use this price to avoid being perceived as a type G firm.

Based on Assumption 3 ($E(\delta_i) > k > 0$) and the fact $d_T - d_G\sqrt{h_G/h_T} > d_T - d_G = E(\delta_i)$, we obtain the following inequality:

$$\begin{aligned} &0.5 \left\{ d_T + c_G + \sqrt{(d_T - c_G)^2 - \frac{h_G}{h_T} (d_G - c_G)^2} \right\} \\ &\quad > 0.5 \left\{ d_T + c_T - \sqrt{(d_T - c_T)^2 - \frac{h_G}{h_T} (d_G - c_T)^2} \right\}. \end{aligned} \tag{A.2}$$

And hence T-type firm's best response belongs to the following interval:

$$\begin{aligned} &\left[0.5 \left\{ d_T + c_G + \sqrt{(d_T - c_G)^2 - \frac{h_G}{h_T} (d_G - c_G)^2} \right\}, \right. \\ &\quad \left. 0.5 \left\{ d_T + c_T + \sqrt{(d_T - c_T)^2 - \frac{h_G}{h_T} (d_G - c_T)^2} \right\} \right]. \end{aligned} \tag{A.3}$$

The key question is whether $(c_T + d_T)/2$ belongs to the interval above. If yes, then T-type firm's best response is $(c_T + d_T)/2$ because it leads to maximized profits. However, if $(c_T + d_T)/2$ does not belong to the interval above, then T-type firm's best response turns to be the floor price of the interval above, that is, $0.5\{d_T + c_G + \sqrt{(d_T - c_G)^2 - (h_G/h_T)(d_G - c_G)^2}\}$.

The fact is $p_{TT} = (c_T + d_T)/2 < 0.5\{d_T + c_G + \sqrt{(d_T - c_G)^2 - (h_G/h_T)(d_G - c_G)^2}\}$ because of Assumption 3, which means p_{TT} is not high enough to distinguish the T-type firm from the G-type firm.

Thus, given $E(p^*)$, in the separating equilibrium, T-type firm's best response is $p_T(E(p^*)) = 0.5(d_T + \sqrt{d_T^2 - (h_G/h_T)d_G^2})$, while G-type firm's best response is $p_G(E(p^*)) = d_G/2$. The definition of d_v yields $E(\delta) = d_T - d_G$. Therefore $p_T(E(p^*)) - p_G(E(p^*)) = 0.5(E(\delta) + \sqrt{d_T^2 - (h_G/h_T)d_G^2}) > 0$, which means the own-price and the expected rival's price are strategic complements. □

Proof of Proposition 6. Profits Π_{uv} would be maximized when $p_{uv} = (c_u + d_v)/2$ and accordingly the maximum profits $\max(\Pi_{uv}) = h_v(d_v - c_u)^2/4$. Since c_u is an increasing function of the true product type and d_v is an increasing function of the perceived product type, the prices p_{uv} have the following relationship: $p_{TT} > p_{GT} > p_{GG}$, and $p_{TT} > p_{TG} > p_{GG}$.

Based on the fact $E(\delta_i) = d_T - d_G$ and Assumption 3, we obtain $d_T - d_G > c_T - c_G = k$ and $p_{GT} > p_{TG}$. Therefore the prices p_{uv} are ordered as follows: $p_{TT} > p_{GT} > p_{TG} > p_{GG}$. □

Proof of Proposition 8. Each firm plays its best response according to its own type, given the rival's pricing strategy. Then based on the definition of $E(p^*)$ and Lemma 7, we know the expected price $E(p^*)$ in the separating equilibrium is a solution to the following equation:

$$\begin{aligned} X &= \lambda p_T(X) + (1-\lambda) p_G(X) \\ &= \frac{\lambda d_T}{2} \\ &+ \left(\frac{\lambda}{2}\right)\sqrt{\left(d_T + \sqrt{\frac{h_G}{h_T}} d_G\right)\left(d_T - \sqrt{\frac{h_G}{h_T}} d_G\right)} \\ &+ \frac{(1-\lambda) d_G}{2}. \end{aligned} \quad (A.4)$$

Substituting d_T and d_G into the equation above, we obtain

$$\begin{aligned} X &= \frac{S+\eta X}{2} + \frac{\lambda}{2} E(\delta) \\ &+ \lambda \left\{ \left[\left(1 + \sqrt{\frac{h_G}{h_T}}\right) \frac{S+\eta X}{2} + \frac{E(\delta)}{2} \right] \right. \\ &\left. \cdot \left[\left(1 - \sqrt{\frac{h_G}{h_T}}\right) \frac{S+\eta X}{2} + \frac{E(\delta)}{2} \right] \right\}^{1/2}, \end{aligned} \quad (A.5)$$

where $S \equiv \alpha - E(\delta) - \gamma[\alpha - (1-\lambda)E(\delta)]/(\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta))$, and $\eta \equiv \gamma/(\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta))$.

Let $Y \equiv (S+\eta X)/2$, then $X = (2Y - S)/\eta$, and (A.5) can be rewritten as

$$\begin{aligned} &Y\left(\frac{2}{\eta} - 1\right) - \frac{S}{\eta} - \frac{\lambda}{2} E(\delta) \\ &= \lambda \left\{ \left[\left(1 + \sqrt{\frac{h_G}{h_T}}\right) Y + \frac{E(\delta)}{2} \right] \right. \\ &\left. \cdot \left[\left(1 - \sqrt{\frac{h_G}{h_T}}\right) Y + \frac{E(\delta)}{2} \right] \right\}^{1/2}. \end{aligned} \quad (A.6)$$

Note that $p_G(E(p^*)) = d_G/2 = Y$.

Let

$$\begin{aligned} \omega &\equiv \left\{ \left[\left(1 + \sqrt{\frac{h_G}{h_T}}\right) Y + \frac{E(\delta)}{2} \right] \right. \\ &\left. \cdot \left[\left(1 - \sqrt{\frac{h_G}{h_T}}\right) Y + \frac{E(\delta)}{2} \right] \right\}^{1/2} \\ &= \sqrt{\left(1 - \frac{h_G}{h_T}\right) Y^2 + E(\delta) Y + \frac{E^2(\delta)}{4}}, \end{aligned} \quad (A.7)$$

and then $p_T(E(p^*)) = d_T/2 + \omega$ and $p_T(E(p^*)) - p_G(E(p^*)) = \omega + E(\delta)/2 > 0$.

Equation (A.6) can be written as

$$\xi_1 Y^2 + \xi_2 Y + \xi_3 = 0, \quad (A.8)$$

where $\xi_1 = (2/\eta - 1)^2 - \lambda^2(1 - h_G/h_T)$, $\xi_2 = -(4/\eta - 2)(S/\eta) - \lambda(2/\eta - 1)E(\delta) - \lambda^2 E(\delta)$, and $\xi_3 = (S/\eta)\lambda E(\delta) + (S/\eta)^2$.

Obviously the coefficient ξ_2 is negative while ξ_3 is positive. Next we infer the sign of the coefficient ξ_1.

$$\xi_1 = \left(\frac{2}{\eta} - 1\right)^2 - \lambda^2 \left(1 - \frac{h_G}{h_T}\right), \quad (A.9)$$

where $S \equiv \alpha - E(\delta) - \gamma[\alpha - (1-\lambda)E(\delta)]/(\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta))$, $\eta \equiv \gamma/(\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta))$,

$$\begin{aligned} h_G &= \frac{\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta)}{[\beta + \tau \,\mathrm{var}(\delta)]\left[\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta)\right] - \gamma^2}, \\ h_T &= \frac{\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta)}{\beta\left[\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta)\right] - \gamma^2}. \end{aligned} \quad (A.10)$$

Obviously ξ_1 is the decreasing function of λ under the assumption of $\beta > \gamma$.

$$\begin{aligned} \min \xi_1 &= \xi_1 \mid (\lambda = 0) = \left(\frac{2}{\eta} - 1\right)^2 > 0, \\ \max \xi_1 &= \xi_1 \mid (\lambda = 1) = \frac{4\beta(\beta+\gamma)(\beta-\gamma)^2 + \gamma^2(\beta+\gamma)(\beta-\gamma) + 4\beta^2\tau \,\mathrm{var}(\delta)(\beta-\gamma)}{\gamma^2\{\beta[\beta + \tau \,\mathrm{var}(\delta)] - \gamma^2\}} > 0, \end{aligned} \quad (A.11)$$

and hence $\xi_1 > 0$. According to $\xi_1 > 0$, $\xi_2 < 0$, and $\xi_3 > 0$, we infer that (A.8) has two positive roots.

$$\begin{aligned} &Y^* \\ &= \frac{(4/\eta - 2)(S/\eta) + \lambda(2/\eta - 1)E(\delta) + \lambda^2 E(\delta)}{2\left[(2/\eta - 1)^2 - \lambda^2(1 - h_G/h_T)\right]} \end{aligned}$$

$$\pm \frac{\sqrt{\left[(4/\eta-2)(S/\eta)+\lambda(2/\eta-1)E(\delta)+\lambda^2E(\delta)\right]^2-4\left[(2/\eta-1)^2-\lambda^2(1-h_G/h_T)\right]\left[(S/\eta)\lambda E(\delta)+(S/\eta)^2\right]}}{2\left[(2/\eta-1)^2-\lambda^2(1-h_G/h_T)\right]}, \tag{A.12}$$

where

$$\begin{aligned} S &\equiv \alpha - E(\delta) - \frac{\gamma\left[\alpha-(1-\lambda)E(\delta)\right]}{\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)}, \\ \eta &\equiv \frac{\gamma}{\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)}, \\ 1-\frac{h_G}{h_T} &= \frac{\tau\operatorname{var}(\delta)\left[\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)\right]}{\left[\beta+\tau\operatorname{var}(\delta)\right]\left[\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)\right]-\gamma^2}. \end{aligned} \tag{A.13}$$

We can derive ω according to the fact $\omega = \sqrt{(1-h_G/h_T)Y^2+E(\delta)Y+E^2(\delta)/4}$. We noted above that $p_G(E(p^*)) = d_G/2 = Y$ and $p_T(E(p^*)) = d_T/2+\omega = Y+\omega+E(\delta)/2$. And hence the equilibrium prices of GM food and conventional food are $p_G = Y^*$ and $p_T = Y^*+\omega^*+E(\delta)/2$, respectively. The price of conventional food is significantly higher than that of GM food in terms of separating equilibrium, and additionally the price gap between the traditional food and GM food is positively correlated to the expected net potential damage $E(\delta)$ because of the positive correlation between ω^* and $E(\delta)$.

Therefore there exist two different separating perfect Bayesian equilibriums consisting of a pair of prices (P_G, P_T) with $P_G < P_T$ and supporting beliefs $B(p^*)$, with $B(p^*) = 1$ if $p \geq P_T$, and $B(p^*) = 0$ if $p < P_T$. □

Proof of Proposition 9. In the separating perfect Bayesian equilibrium, two firms' quantities are $Q_G = h_GY^*$ and $Q_T = h_T(d_T - p_T) = h_T(Y^* + E(\delta)/2 - \omega^*)$, respectively. $Q_T/Q_G = (h_T(Y^* + E(\delta)/2 - \omega^*)/h_GY^*)(E(\delta)/2) - \omega^* < 0$, $h_G/h_T < 1$, and hence the sign of $(Q_T/Q_G - 1)$ depends on $(\omega^* - 0.5E(\delta))/Y^*$ and $(1-h_G/h_T)$. $Q_T < Q_G$ holds if $(\omega^*-0.5E(\delta))/Y^* > 1-h_G/h_T$; $Q_T > Q_G$ holds if $(\omega^* - 0.5E(\delta))/Y^* < 1-h_G/h_T$. According to the proof of Proposition 8, we know the equilibrium prices of GM food and conventional food are $p_G = Y^*$ and $p_T = Y^* + \omega^* + E(\delta)/2$, respectively. It means that, in the separating perfect Bayesian equilibrium, $Q_T < Q_G$ holds if $(p_T - p_G - E(\delta))/p_G > 1 - h_G/h_T$; $Q_T > Q_G$ holds if $(p_T - p_G - E(\delta))/p_G < 1 - h_G/h_T$. □

Proof of Proposition 10. In the equilibrium, two firms' profits are $\Pi_T = (Y^* + E(\delta)/2 + \omega^* - k)h_T(Y^* + E(\delta)/2 - \omega^*)$ and $\Pi_G = h_G(Y^*)^2$, respectively.

As for the G-type firm, obviously its profit (Π_G) is an increasing function of Y^* or the price of GM food since $Y^* > 0$ and $\partial\Pi_G/\partial Y^* > 0$ always holds. As for the T-type firm, substitution of ω^* in terms of Y^* and simplification yield the following form in Y^*:

$$\begin{aligned} \Pi_T &= \left(Y^*+\frac{E(\delta)}{2}+\omega^*-k\right)h_T\left(Y^*+\frac{E(\delta)}{2}-\omega^*\right) \\ &= \left(1-\frac{h_G}{h_T}\right)^2 Y^{*4} + 2E(\delta)\left(1-\frac{h_G}{h_T}\right)Y^{*3} \\ &\quad + \left[1+E^2(\delta)+\left(\frac{E^2(\delta)}{2}-k\right)\left(1-\frac{h_G}{h_T}\right)\right]Y^{*2} \\ &\quad + \left[E(\delta)-k+\left(\frac{E^2(\delta)}{2}-k\right)E(\delta)\right]Y^* \\ &\quad + \left(\frac{E^2(\delta)}{4}-\frac{E(\delta)}{2}\right)\left(\frac{E^2(\delta)}{4}+\frac{E(\delta)}{2}-k\right). \end{aligned} \tag{A.14}$$

Based on Assumption 1, we know Π_T increases as Y^* since $Y^* > 0$ and $\partial\Pi_T/\partial Y^* > 0$ always holds. Hence, the profits of the G-type firm and the T-type firm are both monotonically increasing in the price of GM food. □

Proof of Proposition 11. Although (A.8) has two positive roots, which one is the optimal solution? The answer depends on the profits and the basic utility α.

Proposition 10 shows the profits functions of the G-type firm and the T-type firm both monotonically increase as the price of GM food. Therefore, in terms of the principle of maximizing profits, the bigger Y^* is the optimal solution; that is,

$$\begin{aligned} Y^* &= \frac{(4/\eta-2)(S/\eta)+\lambda(2/\eta-1)E(\delta)+\lambda^2E(\delta)}{2\left[(2/\eta-1)^2-\lambda^2(1-h_G/h_T)\right]} \\ &\quad + \frac{\sqrt{\left[(4/\eta-2)(S/\eta)+\lambda(2/\eta-1)E(\delta)+\lambda^2E(\delta)\right]^2-4\left[(2/\eta-1)^2-\lambda^2(1-h_G/h_T)\right]\left[(S/\eta)\lambda E(\delta)+(S/\eta)^2\right]}}{2\left[(2/\eta-1)^2-\lambda^2(1-h_G/h_T)\right]}. \end{aligned} \tag{A.15}$$

And hence the separating perfect Bayesian equilibrium consisting of a pair of the larger prices (P_G^*, P_T^*) is the first-best solution if $P_G^* < P_T^* < \alpha$, while the smaller prices (P_G^*, P_T^*) are the first-best solution if $P_T^* \geq P_G^* \geq \alpha$. □

Next we prove the larger $P_G^* \geq \alpha$ holds if γ is small enough. Obviously the smaller P_G^* is smaller than $((4/\eta - 2)(S/\eta) + \lambda(2/\eta - 1)E(\delta) + \lambda^2 E(\delta))/2[(2/\eta - 1)^2 - \lambda^2(1 - h_G/h_T)]$, while the larger P_G^* is larger than $((4/\eta - 2)(S/\eta) + \lambda(2/\eta - 1)E(\delta) + \lambda^2 E(\delta))/2[(2/\eta - 1)^2 - \lambda^2(1 - h_G/h_T)]$.

Since S can be rewritten as $\alpha - E(\delta) - \eta[\alpha - (1-\lambda)E(\delta)]$ and $1 - h_G/h_T$ can be expressed as $\tau\,\mathrm{var}(\delta)/([\beta + \tau\,\mathrm{var}(\delta)] - \eta\gamma)$, $(4/\eta - 2)(S/\eta) + \lambda(2/\eta - 1)E(\delta) + \lambda^2 E(\delta)/2[(2/\eta - 1)^2 - \lambda^2(1 - h_G/h_T)]$ will be equal to $((2 - 3\eta + \eta^2)\alpha + [3\eta - \lambda\eta - 2 - \eta^2(1 + \lambda/2 + \lambda^2/2)]E(\delta))/\eta^2[(2/\eta - 1)^2 - \lambda^2(\tau\,\mathrm{var}(\delta)/((\beta + \tau\,\mathrm{var}(\delta)) - \eta\gamma))] \equiv \Psi$. When the degree of product substitution γ is small enough (i.e., the difference between the conventional food and GM food is large enough), we can obtain $\eta \rightarrow 0$ and hence the numerator of Ψ converges to $2(\alpha - E(\delta))$ and the denominator converges to 0. Therefore $\Psi \rightarrow \infty$. Therefore the larger $P_G^* > \Psi > \alpha$ holds when the difference between the conventional food and GM food is large enough.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] T. Yaseen, D.-W. Sun, and J.-H. Cheng, "Raman imaging for food quality and safety evaluation: Fundamentals and applications," *Trends in Food Science & Technology*, vol. 62, pp. 177–189, 2017.

[2] J. Zhou, Z. Yan, and Y. Wang, "Improving quality and safety of aquatic products: A case study of self-inspection behavior from export-oriented aquatic enterprises in Zhejiang Province, China," *Food Control*, vol. 33, no. 2, pp. 528–535, 2013.

[3] K. G. Grunert, "Food quality and safety: consumer perception and demand," *European Review of Agricultural Economics*, vol. 32, no. 3, pp. 369–391, 2005.

[4] L. Zhao, H. Gu, C. Yue, and D. Ahlstrom, "Consumer welfare and GM food labeling: a simulation using an adjusted Kumaraswamy distribution," *Food Policy*, vol. 42, pp. 58–70, 2013.

[5] A. Hino, "Safety assessment and public concerns for genetically modified food products: the japanese experience," *Toxicologic Pathology*, vol. 30, no. 1, pp. 126–128, 2002.

[6] M. Valente and C. Chaves, "Perceptions and valuation of GM food: A study on the impact and importance of information provision," *Journal of Cleaner Production*, 2017.

[7] S. Jin, Y. Zhang, and Y. Xu, "Amount of information and the willingness of consumers to pay for food traceability in China," *Food Control*, vol. 77, pp. 163–170, 2017.

[8] S. M. N. Khalid, "Food safety and quality management regulatory systems in Afghanistan: Policy gaps, governance and barriers to success," *Food Control*, vol. 68, pp. 192–199, 2016.

[9] L. Zhao, C. Wang, H. Gu, and C. Yue, "Market incentive, government regulation and the behavior of pesticide application of vegetable farmers in China," *Food Control Forthcoming*, 2017.

[10] L. J. Mirman and M. Santugini, "Learning and technological progress in dynamic games," *Dynamic Games and Applications*, vol. 4, no. 1, pp. 58–72, 2014.

[11] L. Marian, P. Chrysochou, A. Krystallis, and J. Thøgersen, "The role of price as a product attribute in the organic food context: An exploration based on actual purchase data," *Food Quality and Preference*, vol. 37, pp. 52–60, 2014.

[12] A. Dubovik and M. C. Janssen, "Oligopolistic competition in price and quality," *Games and Economic Behavior*, vol. 75, no. 1, pp. 120–138, 2012.

[13] S. Liu, D. Zhang, R. Zhang, and B. Liu, "Analysis on RFID operation strategies of organic food retailer," *Food Control*, vol. 33, no. 2, pp. 461–466, 2013.

[14] M. N. Hertzendorf and P. B. Overgaard, "Price competition and advertising signals: Signaling by competing senders," *Journal of Economics & Management Strategy*, vol. 10, no. 4, pp. 621–662, 2001.

[15] C. Fluet and P. G. Garella, "Advertising and prices as signals of quality in a regime of price rivalry," *International Journal of Industrial Organization*, vol. 20, no. 7, pp. 907–930, 2002.

[16] R. Orzach and Y. Tauman, "Signalling reversal," *International Economic Review*, vol. 37, no. 2, pp. 453–464, 1996.

[17] K. Bagwell and M. H. Riordan, "High and declining prices signal product quality," *American Economic Review*, vol. 81, no. 1, pp. 224–239, 1991.

[18] A. F. Daughety and J. F. Reinganum, "Product safety: liability, RD, and signaling," *The American Economic Review*, pp. 1187–1206, 1995.

[19] L. J. Mirman, E. M. Salgueiro, and M. Santugini, "Noisy signaling in monopoly," *International Review of Economics & Finance*, vol. 29, pp. 504–511, 2014.

[20] M. C. Janssen and S. Roy, "Signaling quality through prices in an oligopoly," *Games and Economic Behavior*, vol. 68, no. 1, pp. 192–207, 2010.

[21] W. Daher, L. J. Mirman, and M. Santugini, "Information in Cournot: Signaling with incomplete control," *International Journal of Industrial Organization*, vol. 30, no. 4, pp. 361–370, 2012.

[22] F. Adriani and L. G. Deidda, "Competition and the signaling role of prices," *International Journal of Industrial Organization*, vol. 29, no. 4, pp. 412–425, 2011.

[23] A. F. Daughety and J. F. Reinganum, "Communicating quality: A unified model of disclosure and signalling," *The RAND Journal of Economics*, vol. 39, no. 4, pp. 973–989, 2008.

[24] M. C. Janssen and S. Roy, "Strategic Disclosure and Signaling of Product Quality with Price Competition," in *Proceedings of the trategic Disclosure and Signaling of Product Quality with Price Competition. In 38th EARIE Conference*, pp. 1–3, 2011.

[25] L. Levidow, "Precautionary uncertainty: Regulating GM crops in Europe," *Social Studies of Science*, vol. 31, no. 6, pp. 842–874, 2001.

[26] A. I. Myhr and T. Traavik, "The precautionary principle: Scientific uncertainty and omitted research in the context of GMO use and release," *Journal of Agricultural and Environmental Ethics*, vol. 15, no. 1, pp. 73–86, 2002.

[27] A. Cockburn, "Assuring the safety of genetically modified (GM) foods: The importance of an holistic, integrative approach," *Journal of Biotechnology*, vol. 98, no. 1, pp. 79–106, 2002.

[28] A. F. Daughety and J. F. Reinganum, "Imperfect competition and quality signalling," *The RAND Journal of Economics*, vol. 39, no. 1, pp. 163–183, 2008.

[29] D. J. Johnstone and D. V. Lindley, "Elementary proof that mean-variance implies quadratic utility," *Theory and Decision. An International Journal for Multidisciplinary Advances in Decision Science*, vol. 70, no. 2, pp. 149–155, 2011.

[30] H. Dong, W. Li, W. Tang, and D. Zhang, "Development of hybrid Bt cotton in China - A successful integration of transgenic technology and conventional techniques," *Current Science*, vol. 86, no. 6, pp. 778–782, 2004.

[31] M. Costa-Font, R. B. Tranter, and J. M. Gil, "Consumers' Opinions and Attitudes Towards Co-existence of GM and Non-GM Food Products," *Genetically Modified and Non-Genetically Modified Food Supply Chains: Co-Existence and Traceability*, pp. 113–126, 2012.

[32] Y. Li, N. M. Ashkanasy, and D. Ahlstrom, "The rationality of emotions: A hybrid process model of decision-making under uncertainty," *Asia Pacific Journal of Management*, vol. 31, no. 1, pp. 293–308, 2014.

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Research Article

Economic Order Quality Model for Determining the Sales Prices of Fresh Goods at Various Points in Time

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Although the safe consumption of goods such as food products, medicine, and vaccines is related to their freshness, consumers frequently understand less than suppliers about the freshness of goods when they purchase them. Because of this lack of information, apart from sales prices, consumers refer only to the manufacturing and expiration dates when deciding whether to purchase and how many of these goods to buy. If dealers could determine the sales price at each point in time and customers' intention to buy goods of varying freshness, then dealers could set an optimal inventory cycle and allocate a weekly sales price for each point in time, thereby maximizing the profit per unit time. Therefore, in this study, an economic order quality model was established to enable discussion of the optimal control of sales prices. The technique for identifying the optimal solution for the model was determined, the characteristics of the optimal solution were demonstrated, and the implications of the solution's sensitivity analysis were explained.

1. Introduction

Previous studies have demonstrated the relevance of food freshness and consumer utility. Although consumers judge food freshness through the senses [1–4] and through labels containing information on the manufacture and expiration date, the freshness information available to consumers remains asymmetrical. This asymmetry usually originates from how retailers perform (1) fresh food replenishment and (2) relabeling. When retailers replenish their goods, their shelves contain the same goods with differing expiration dates, and the retailers' clever arrangement and stacking of the goods render consumers more likely to access those with closer expiration dates. In practice, retailers offer discounts on fresh goods with closer expiration dates, thus requiring the goods to be relabeled. Many supermarkets employ fixed percentage labeling (such as 20% discounts) to affect consumers' purchase behaviors. However, the relabeling of fresh goods may involve human error factors (even tampering with expiration dates). Therefore, numerous supermarkets in Europe, the United States, and Japan employ label management models containing expiration dates based on the label dates and solar dates, although this also leads to freshness information gaps between consumers and retailers. In addition, some chain retailers adopt the same price discounts for expiring fresh goods (e.g., Taiwan's PX Mart supermarket chain offering 20% discounts for expiring fresh goods) while overlooking various factors relating to consumers' demands for goods with differing expiration dates (degree of freshness). This practice is clearly inappropriate. Such neglect has a significant impact on consumers' price discrimination and retailers' expected profits [5, 6]. If dealers can determine the sales price at each point in time and customers' intention to buy food of varying freshness, then dealers can set an optimal inventory cycle and allocate a weekly sales price for each point in time, thereby maximizing the profit per unit time.

The research frameworks for studying the inventory optimization problems of fresh (or perishable) goods tend to be highly complex because the freshness of goods affects consumer utility and thus their demands. The earliest literature review on the inventory model for deteriorating items was a review of inventory models for perishable goods conducted by Nahmias [7], which was expanded by Goyala and Giri [8]. Literature reviews published from 2011 to 2016 have treated fresh (or perishable) goods as a distinct classification and examined relevant research. For detailed literature reviews on the inventory model for deteriorating items, see Nahmias [9], Karaesmen et al. [10], Bakker et al. [11], and Janssen et al. [12]. This study avoided repeating these previous works and instead focused on a deeper exploration of the problems involved in fresh goods inventories.

The traditional economic order quantity (EOQ) model was designed to solve the problem encountered by buy-in and sell-out dealers, who determine the inventory standard of goods at the beginning of each period in response to the given demand rate of goods, thereby minimizing the cost per unit time. To expand the applications of the conventional EOQ model, various types of extended inventory models have been developed by inventory management scholars in recent years in their studies on fresh (or perishable) goods inventories. According to loosened assumptions, these extended models (some of which can be categorized as hybrid models comprising more than one type) can be divided into the following types.

Type 1. The assumption of the traditional EOQ model has been relaxed from "the demand rate is a given constant" to "the demand rate varies according to time" [13–32].

Type 2. The assumption of the traditional EOQ model has been changed from "goods are nondegenerative" to "goods are degenerative goods (e.g., petroleum and other volatile products) that decrease in volume over time even when unsold" [33–36]. Since 2010, an increasing number of studies on deteriorating goods inventory have focused on fresh (perishable) goods whose quality deteriorates over time [25, 37–48].

Type 3. The assumption of the traditional EOQ model has been changed from "the unit prices of the goods acquired (purchased) by dealers are a fixed constant" to "unit prices may be affected by lot size owing to volume discounts" [14, 49–56].

Type 4. The assumption of the traditional EOQ model has been relaxed from "sales prices are a given constant (fixed demand rate)" to "sales prices are a decision variable for dealers" [25, 38, 50, 57–73].

Numerous inventory models for fresh (or perishable) goods have been proposed in the past 20 years, with pricing problems being one of the most extensively researched topics in the past 10 years. Most research on pricing problems has concentrated on discount optimization; only a few scholars have specifically studied dynamic price optimization, and most of which studies have been conducted in the past 5-6 years [25, 38, 67–73]. In this study, goods dealers were assumed to possess the opportunity and capability to determine sales prices at each point in time (sales prices are the decision variable for goods dealers). This assumption supports the Type 4 EOQ model, which posits that dealers may decide the sales prices at each point in time, in comparison to the traditional model that states dealers may determine only one sales price standard.

2. Mathematical Model

2.1. Parameters

e: time at which goods expire. Specifically, e represents the duration from the time of goods purchase ($t = 0$) to the time of their expiration.

h: storage cost of a unit of goods within a unit time.

c: purchase price of a unit of goods.

A: setup cost.

2.2. Given Functions

$d = d(p(t))$: the potential demand rate for goods as reflected by customer reaction to the sales price p, where $d(p(t)) > 0$. A potential demand rate indicates the demand rate for goods when customers became aware of the sales price $p(t)$ at the point in time t but are not aware of or have not considered the expiration time e. In this study, a linear function of the sales price $p(t)$ at the point in time t was established as follows:

$$d(p(t)) = a - bp(t), \quad p(t) \in \left[0, \frac{a}{b}\right]. \tag{1}$$

a: maximal limit of the potential demand rate, where $a > 0$.

a/b: maximal limit of $p(t)$. This means that, at the point of time t,

$$\begin{gathered} \text{when } p(t) \text{ decreases to zero, } d(p(t)) \text{ increases to } a \\ \text{when } p(t) \text{ increases to } \frac{a}{b}, \ d(p(t)) \text{ decreases to zero.} \end{gathered} \tag{2}$$

$r = r(t)$: the intentions of consumers to purchase goods when consumers enter the place of sale at point in time t, learn about the sales price $p(t)$, become potential demanders for the goods, and find that the remaining time until the goods' expiration is $(e - t)$. In particular, $r(t) \in [0, 1]$ is the linear decreasing function of $t, t \in [0, e)$, and satisfies $r(0) = 1$ and $r(t) = 0, \ \forall t \geq e$.

Thus

$$r(t) = \begin{cases} \dfrac{e - t}{e}, & \text{when } t \in [0, e) \\ 0, & \text{when } t \geq e. \end{cases} \tag{3}$$

2.3. Decision Variables

$p = p(t)$: sales price at the point in time t, where $p(t) \in [0, a/b], \ \forall t$.

$x = x(t)$: inventory standard at t, where $x(t)$ is the decreasing function of t in the inventory period $[0, T_x]$ corresponding to x, and $x(T_x) = 0$.

T_x: duration of the inventory cycle corresponding to the dealer decision variable x. Because e represents the expiration time of the goods, T_x corresponding to the target function x must fulfill the following inequality:

$$T_x \leq e. \tag{4}$$

L_x: per unit time profit of the dealer's decision variable x corresponding to the inventory cycle T_x; that is,

$$L_x = \frac{1}{T_x}\left[\text{dealer's profit within one inventory cycle } T_x\right]. \tag{5}$$

$-x'(t)$: sales rate of the goods corresponding to x at the point in time t.

From (1) and (3), the following is obtained:

$$-x'(t) = d(p(t)) \cdot r(t) = (a - bp(t)) \cdot \frac{e-t}{e}. \tag{6}$$

Because $p(t) \in [0, a/b]$, the following can be obtained from the preceding equation:

$$\frac{-x'(t)e}{e-t} = a - bp(t) \in [0, a], \quad \forall t \in [0, T_x]. \tag{7}$$

From (7), the following can be obtained:

$$p(t) = \frac{ex'(t)}{b(e-t)} + \frac{a}{b}, \quad t \in [0, T_x] \leq [0, e]. \tag{8}$$

Through (7) and (8), the mathematical model that dealers can use to determine the decision variable x to maximize the profit per unit time corresponding to x is established as follows:

$$\begin{aligned}
&\max_x \quad L(x) = \frac{1}{T_x}\left\{\left[\int_0^{T_x}\left(\frac{ex'(t)}{b(e-t)} + \frac{a}{b}\right)(-x'(t)) - hx(t)\right]dt - cx(0) - A\right\}. \\
&\text{s.t.} \quad x'(t) \text{ exists as the continuous function of } [0, T_x]; \\
&\qquad \frac{-x'(t)e}{e-t} \in [0, a], \quad \forall t \in [0, T_x];\ x(T_x) = 0;\ x(0) \text{ exhibits freedom} \\
&\qquad (\text{that is } x(0) \text{ varies according to the feasible solution } x)
\end{aligned} \tag{9}$$

3. Optimal Solution of Model (9)

Assume $x^* = x^*(t)$, $t \in [0, T_{x^*}]$ is the optimal solution of (9). The required conditions of x are obtained in the following procedures.

T_x corresponding to the feasible solution $x = x(t)$ in (9) must fulfill the following inequality:

$$p(T_x) - (c + T_x h) \geq 0. \tag{10}$$

If $[p(T_x) - (c + T_x h)] < 0$, then dealers can reduce the initial amount of purchase at $t = 0$ and shorten the inventory cycle T_x, thereby maximizing the profit.

Because the objective function of (10) is exceptional (the integral value must be divided by T_x) and the feasible solution must fulfill the constraint that $-x'(t)e/(e-t) \in [0, a]$, $\forall t \in [0, T_x]$, (9) becomes a nonstandard calculus of variation problem. Identifying the conditions required for the optimal solution to this problem is the focus of this section.

To solve (9), it was divided into two problems, namely, (11) and (13). Given the T value, let $\overline{x}_T(t)$ be the optimal solution of (11) and L_T the target value of the optimal solution; that is,

$$\begin{aligned}
&L_T = \max_x \quad \frac{1}{T}\left\{\left[\int_0^{T}\left(\frac{ex'(t)}{b(e-t)} + \frac{a}{b}\right)(-x'(t)) - hx(t)\right]dt - cx(0) - A\right\} \\
&\text{s.t.} \quad x'(t) \text{ exists as the continuous function of } [0, T]; \\
&\qquad \frac{-x'(t)e}{e-t} \in [0, a],\ \forall t \in [0, T];\ x(T) = 0;\ x(0) \text{ exhibits freedom;} \\
&\qquad \text{and } T \text{ value is given.}
\end{aligned} \tag{11}$$

Let $\overline{x}_T(t)$ be the optimal solution of (11); the difference between (9) and (11) is as follows: the period of a cycle in the feasible solutions x to problem (11) equals the given T value, and the function $\overline{x}_T(t)$ and target value L_T of the optimal solution vary according to the given T value. If the given T value in (11) is applied as the period T^* of the function $x^*(t)$ of the optimal solution to (9) (let $T = T^*$, and substitute it into (11)), as seen, the optimal solution of (9) will also be the optimal solution of (11); that is,

$$\overline{x}_{T^*}(t) = x^*(t), \quad \forall t \in [0, T^*]. \tag{12}$$

Compared with (9) and (11), (12) can be employed to obtain T as the optimal solution to (13):

$$L_{T^*} = \max_T L_T. \tag{13}$$

because (11) involves the constraint $-x'(t)e/(e-t) \in [0, a]$, $\forall t \in [0, T_x]$, such that (11) is still a nonstandard calculus of variation problem. Therefore, this constraint was neglected temporarily, and the following standard calculus of variation problem (14) was considered.

$$\begin{aligned} L_T = \max_x \quad & \frac{1}{T}\left\{\left[\int_0^T \left(\frac{ex'(t)}{b(e-t)} + \frac{a}{b}\right)\left(-x'(t)\right) - hx(t)\right] dt - cx(0) - A\right\} \\ \text{s.t.} \quad & x'(t) \text{ exists as the continuous function of } [0, T_x];\ x(T) = 0; \\ & x(0) \text{ exhibits freedom, and the } T \text{ value is given.} \end{aligned} \tag{14}$$

Applying the existing theory of calculus of variations to this type of problem [74] yields the optimal solution to (14) labeled as $\widehat{x}_T(t)$. The following conditions must be fulfilled.

The condition of the Euler equation:

$$-h = \frac{d}{dt}\left[\frac{-2e}{b-(e-t)} \cdot \widehat{x}_T(t) - \frac{a}{b}\right]. \tag{15}$$

The condition of $x(0)$ as a target salvage value:

$$\frac{-2}{b} \cdot \widehat{x}'_T(0) - \frac{a}{b} + c = 0, \quad \forall t \in [0, T]. \tag{16}$$

Integrating t with (15) and using (16) yield the following formula:

$$ht + c = \frac{2e}{b(e-t)} \cdot \widehat{x}'_T(t) + \frac{a}{b}, \quad \forall t \in [0, T]. \tag{17}$$

Using (2), (10), and (17), the following is obtained:

$$\frac{-\widehat{x}'_T(t) \cdot e}{e-t} = \frac{b}{2}\left(\frac{a}{b} - c - ht\right) \in [0, a], \quad \forall t \in [0, T]. \tag{18}$$

$$\widehat{x}''_T(t) = \frac{b}{2e}\left[\frac{a}{b} - c - ht + (e-t)h\right] \geq 0. \tag{19}$$

Because the set of feasible solutions for (14) includes those for (11), the feasible solutions x for (11) are also feasible solutions for (14). However, the feasible solutions for (14) may not necessarily be those for (11). Therefore, the optimal solution $\widehat{x}_T$ to (18) has been verified to also be the optimal solution $\widehat{x}_T$ to (11).

Integrating (17) and using $x_T(T) = 0$ yield the following:

$$\begin{aligned} \overline{x}_T(t) &= \widehat{x}_T(t) \\ &= \frac{-b}{2e}\left[\left(\frac{a}{b} - c\right)et - \left(\frac{a}{b} - c + he\right)\frac{t^2}{2} + h\frac{t^3}{3}\right] \\ &\quad + \frac{b}{2e}\left[\frac{a}{b}(-c)eT - \left(\frac{a}{b} - c + he\right)\frac{T^2}{2} + h\frac{t^3}{3}\right], \\ &\quad \forall t \in [0, T]. \end{aligned} \tag{20}$$

By partial integration,

$$\begin{aligned} &\int_0^T -h\overline{x}_T(t)\,dt \text{ is written as } \int_0^T ht\overline{x'}_T(t)\,dt; \\ &-cx(0) \text{ is written as } \int_0^T \overline{x'}_T(t)\,dt. \end{aligned} \tag{21}$$

Using (21) and applying (19) into the objective function (11) yield the following:

$$\begin{aligned} L_T &= \frac{1}{T}\int_0^T \left[\left(\frac{e\overline{x'}_T(t)}{b(e-t)} + \frac{a}{b}\right)\left(-\overline{x'}_T(t)\right) - hx(t)\right] dt \\ &\quad - cx(0) - A \\ &= \frac{1}{T}\left[\int_0^T \left(\frac{e\overline{x'}_T(t)}{b(e-t)} + \frac{a}{b} - c - ht\right)\left(-\overline{x'}_T(t)\right) dt \right. \\ &\quad \left. - A\right]; \quad \text{using (17)} \\ &= \frac{1}{T}\left[\int_0^T \left(\frac{ht + c - a/b}{2} + \frac{a}{b} - c - ht\right)\right. \\ &\quad \left. \cdot \frac{b(e-t)}{2e}\left(\frac{a}{b} - c - ht\right) dt - A\right] \\ &= \frac{1}{T}\left[\int_0^T \frac{b}{4e}(e-t)\left(\frac{a}{b} - c - ht\right)^2 dt - A\right]. \end{aligned} \tag{22}$$

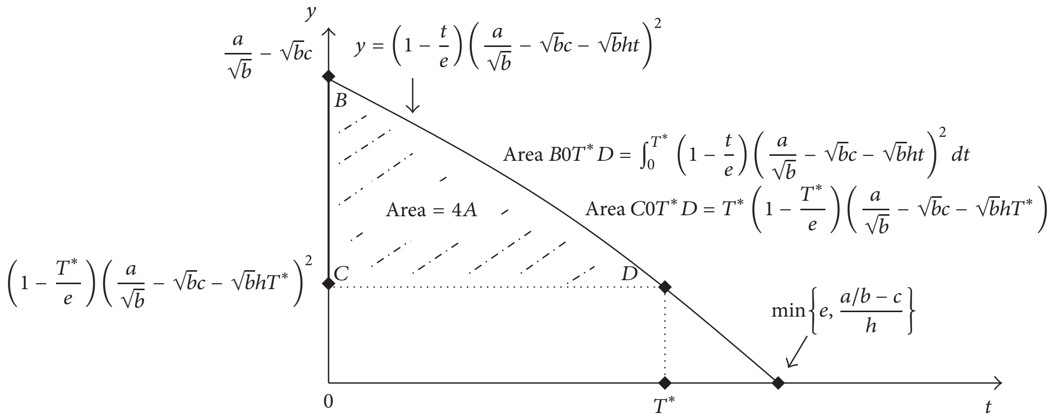

FIGURE 1: The optimal inventory cycle T^*.

From (22), the optimal solution T^* to (13) is acquired. The following conditions must be satisfied (see Appendix A for details):

$$\begin{aligned}
0 &= \frac{d}{d_T}L_T\bigg|_{T^*} = \frac{b}{4eT^*}\left(e - T^*\right)\left(\frac{a}{b} - c - hT^*\right)^2 \\
&\quad - \frac{1}{T^{*2}}\left[\int_0^{T^*}\frac{b}{4e}\left(e - t\right)\times\left(\frac{a}{b} - c - ht\right)^2 dt - A\right] \\
&= \frac{1}{4T^{*2}}\left[T^*\left(1 - \frac{T^*}{e}\right)\right. \\
&\quad \cdot\left(\frac{a}{\sqrt{b}} - \sqrt{b}\cdot c - \sqrt{b}\cdot hT^*\right)^2 - \int_0^{T^*}\left(1 - \frac{t}{e}\right) \\
&\quad \left.\times\left(\frac{a}{\sqrt{b}} - \sqrt{b}\cdot c - \sqrt{b}\cdot ht\right)^2 dt + 4A\right],
\end{aligned} \tag{23}$$

$$\begin{aligned}
\frac{d^2}{d_{T^2}}L_T\bigg|_{T^*} &= \frac{b}{4eT^{*2}}\left[\left(e - 2T^*\right)\left(\frac{a}{b} - c - hT^*\right)^2\right. \\
&\quad + T^*\left(e - T^*\right)\times(-2h)\left(\frac{a}{b} - c - hT^*\right)^2 - \left(e - T^*\right) \\
&\quad \left.\cdot\left(\frac{a}{b} - c - hT^*\right)^2\right] = \frac{-b}{4eT^{*2}}T^*\left(\frac{a}{b} - c - hT^*\right) \\
&\quad \cdot\left[\left(\frac{a}{b} - c - hT^*\right) + 2h\left(e - T^*\right)\right] \\
&\le 0.
\end{aligned} \tag{24}$$

As (2) and (10) reveal, $a/b - c - hT^* \ge 0$; (4) indicates that $e - T^* \ge 0$. Therefore, (24) confirms that

$$\frac{d^2}{d_{T^2}} L_T\big|_{T^*} \le 0. \tag{25}$$

This process indicates the following.

T^* satisfying the first-order conditions of the optimal solutions in (23) must also satisfy the second-order conditions of the optimal solutions in (25).

Figure 1 depicts T^* for (23).

Next, (12), (18), and (20) can be used to obtain the optimal solution x^* of (9):

$$\begin{aligned}
x^*(t) &= \frac{b}{2e}\left[\left(\frac{a}{b} - c\right)\cdot e\left(T^* - t\right)\right. \\
&\quad \left.-\left(\frac{a}{b} - c + he\right)\frac{T^{*2} - t^2}{2} + h\cdot\frac{T^{*3} - t^3}{3}\right], \\
&\qquad t \in \left[0, T^*\right]
\end{aligned} \tag{26}$$

$$x^{*\prime}(t) = \frac{-b}{2e}\left(e - t\right)\left(\frac{a}{b} - c - ht\right), \quad t \in \left[0, T^*\right]. \tag{27}$$

From (27) and (8), the optimal price $p^*(t)$ can be obtained:

$$p^*(t) = \frac{1}{2}\left(\frac{a}{b} + c + ht\right), \quad t \in \left[0, T^*\right]. \tag{28}$$

Problem (28) indicates that the initial optimal sales price for a favorable $p^*(0)$ is $(1/2)(a/b+c)$; the initial unit profit, $p^*(0) - c$, is $(1/2)(a/b - c)$.

Problem (26) reveals that if changes in some of the parameters cause T^* and $x^*(0)$ to change, then the rate of change for these two parameters is expressed as follows:

$$\begin{aligned}
&\frac{dx^*(0)}{d_{T^*}} \\
&\quad = \frac{bh}{2e}\left[T^{*2} + \left(\frac{a/b - c}{h} + e\right)T^* + \frac{a/b - c}{h}\cdot e\right] \\
&\quad = \frac{bh}{2e}\left(T^* - \frac{a/b - c}{h}\right)\left(T^* - e\right) = -x^{*\prime}\left(T^*\right) > 0.
\end{aligned} \tag{29}$$

This function illustrates that the rate of change of the initial inventory standard $x^*(0)$ at the beginning of the inventory cycle of the goods to the optimal inventory period T^* is equal to the sales rate of the goods at the end of the inventory cycle $-x^*(T)$.

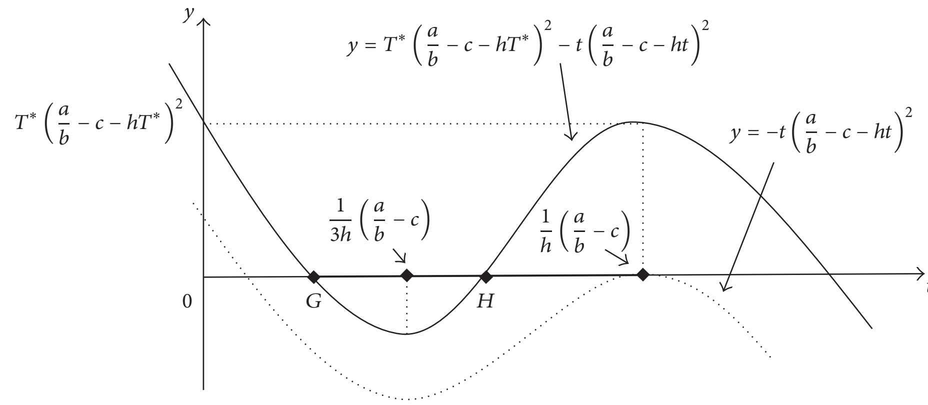

FIGURE 2: Effect of the increase in e on T^*.

4. Sensitivity Analysis of the Optimal Solution $x^*=x^*(t)$

If the sensitivity analysis result of T^* from (26), (27), and (28) is obtained, then the sensitivity analysis result of the optimal inventory function, $x^*(t)$, and the optimal sales price function, $p^*(t)$, can be acquired.

4.1. Effect of Changes in A on T^*. As shown in Figure 1, when A increases, the area of BCD increases, and the curves in the figure remain unchanged. Thus, T^* increases. Therefore,

$$\frac{\partial T^*}{\partial A} > 0. \tag{30}$$

However, T^* is labeled as $T^*(A)$ because it varies according to A in (24). Partially differentiating A with (24) yields the following formula:

$$\begin{aligned}\frac{\partial T^*}{\partial A} &= 4T^{*-1}\left[\left(\frac{a}{\sqrt{b}} - \sqrt{b}c - \sqrt{b}hT^*\right)^2 \cdot \frac{1}{e}\right.\\ &\quad \left. + \left(1 - \frac{T^*}{e}\right) \times 2\left(\frac{a}{\sqrt{b}} - \sqrt{b}c - \sqrt{b}hT^*\right)\sqrt{b}h\right]^{-1}\\ &> 0.\end{aligned} \tag{31}$$

4.2. Effect of Changes in e on T^*. Partially differentiating e with (23) yields the following formula (see Appendix B for details):

$$\begin{aligned}\frac{\partial T^*}{\partial e} &= T^{*\prime}(e)\\ &= \frac{1/e\int_0^{T^*}\left[T^*(a/b - c - hT^*)^2 - t(a/b - c - ht)^2\right]dt}{T^*(a/b - c - hT^*)\left[(a/b - c - hT^*) + 2h(e - T^*)\right]} \qquad (32)\\ &= \frac{1}{12}\left(\frac{a}{b} - c - hT^*\right)^2\left(6T^* + \frac{a/b - c - hT^*}{h}\right)\\ &\quad \times\left(2T^* - \frac{a/b - c - hT^*}{h}\right) + \frac{(a/b - c)^4}{12h^2}. \qquad (33)\end{aligned}$$

The incorporation of (32) and (33) verifies that $\partial T^*/\partial e > 0$. In Scenario (1), assume that T^* is shown at the G point in Figure 2. The numerator of (32) is larger than zero; therefore, $\partial T^*/\partial e > 0$. In Scenario (2), assume that T^* is shown at the H point in Figure 2. Then, (33) reveals that $\partial T^*/\partial e > 0$.

4.3. Effect of Changes in h on T^*. By partially differentiating h with (23), the following formula is obtained (see Appendix C for details):

$$T^{*\prime}(h) = \frac{-2\int_0^{T^*}\left[T^*(e - T^*)(a/b - c - hT^*) - t(e - t)(a/b - c - ht)\right]dt}{T^*(a/b - c - hT^*)^2 + 2T^*(e - T^*)(a/b - c - hT^*)} > 0. \tag{34}$$

4.4. Effect of Changes in c on T^*. Partially differentiating c with (23) yields the following formula (see Appendix D for details):

$$T^{*\prime}(c) = \frac{-2\int_0^{T^*}\left[T^*(e - T^*)(a/b - c - hT^*) - (e - t)(a/b - c - ht)\right]dt}{2hT^*(e - T^*)(a/b - c - hT^*) + T^*(a/b - c - hT^*)^2} \tag{35}$$

(T^* changes; see Figure 4).

5. Conclusions

This study divided the inventory promotion model of fresh goods into four categories and examined published academic journals papers that have investigated these categories, finding that few scholars have studied the dynamic pricing of fresh goods. The EOQ model established in this study enables dealers to determine sales prices at each point in time after the relationship between consumer reactions to the freshness of the goods and purchasing intentions is determined.

The optimal inventory cycle T^* can be obtained from (23), and the implication of T^* is illustrated in Figure 1. Within the optimal inventory cycle $[0, T^*]$, the optimal inventory standard $x^*(t)$ at t is expressed in (26), the optimal sales rate $-x^{*\prime}(t)$ at t is expressed in (27), and the optimal sales price $p^*(t)$ at t is expressed in (28).

We also analyzed the sensitivity of the optimal solution to changes in each variable. The results revealed the following. (a) The optimal inventory cycle T^* and the initial inventory standard $x^*(0)$ both increased as the setup cost A increased; the rate of change is displayed in (31) and (29). (b) T^* and $x^*(0)$ both increased as the expiration time of the goods e increased; the rate of change is shown in (32) and (29). (c) T^* and $x^*(0)$ both decreased as the inventory cost h increased; the rate of change is illustrated in (34) and (29). (d) T^* and $x^*(0)$ both increased as the unit purchase price c increased; the rate of change is depicted in (35) and (29).

The main contribution of this research model to management is the incorporation of consumers' demand response to the manufacture and expiration dates (or degree of freshness) of fresh goods. Retailers tend to have both old and new goods on their shelves when replenishing fresh goods—that is, they stock same goods with differing expiration dates. They may even have differing expiration dates despite having the same manufacture dates because of environmental factors such as transportation and storage. Therefore, retailers can set the prices at different time points of the goods' shelf life instead of adopting a straightforward price discount as in the past, which may cause them to lose part of their expected profits. Using the parameters to determine the rate of change for the optimal solution can assist fresh goods retailers in conducting immediate price control.

Appendix

A. The Necessary Condition for the Optimal Solution T^*

From (22), the optimal solution T^* to (13) is acquired. The following conditions must be satisfied:

$$
\begin{aligned}
0 &= \frac{d}{d_T} L_T\Big|_{T^*} = \frac{b}{4eT^*}\left(e-T^*\right)\left(\frac{a}{b}-c-hT^*\right)^2 \\
&\quad - \frac{1}{T^{*2}}\left[\int_0^{T^*} \frac{b}{4e}(e-t)\times\left(\frac{a}{b}-c-ht\right)^2 dt - A\right] \\
&= \frac{b}{4eT^{*2}}\left[T^*\left(e-T^*\right)\left(\frac{a}{b}-c-hT^*\right)^2\right. \\
&\quad \left. - \int_0^{T^*}(e-t)\times\left(\frac{a}{b}-c-ht\right)^2 dt + \frac{4eA}{b}\right] \\
&= \frac{1}{4T^{*2}}\left[T^*\left(1-\frac{T^*}{e}\right)\right. \\
&\quad \cdot\left(\frac{a}{\sqrt{b}}-\sqrt{b}\cdot c-\sqrt{b}\cdot hT^*\right)^2 \\
&\quad - \int_0^{T^*}\left(1-\frac{t}{e}\right)\times\left(\frac{a}{\sqrt{b}}-\sqrt{b}\cdot c-\sqrt{b}\cdot ht\right)^2 dt \\
&\quad \left. + 4A\right],
\end{aligned}
\tag{A.1}
$$

$$
\begin{aligned}
\frac{d^2}{d_{T^2}} L_T\Big|_{T^*} &= \frac{b}{4eT^{*2}}\left[\left(e-2T^*\right)\left(\frac{a}{b}-c-hT^*\right)^2\right. \\
&\quad + T^*\left(e-T^*\right)\times(-2h)\left(\frac{a}{b}-c-hT^*\right)^2 \\
&\quad \left. - \left(e-T^*\right)\left(\frac{a}{b}-c-hT^*\right)^2\right] = \frac{-b}{4eT^{*2}}T^*\left(\frac{a}{b}-c\right. \\
&\quad \left. - hT^*\right)\left[\left(\frac{a}{b}-c-hT^*\right)+\left(e-T^*\right)\cdot 2h\right] \\
&= \frac{-b}{4eT^{*2}}T^*\left(\frac{a}{b}-c-hT^*\right)\left(\frac{a}{b}-c+2eh\right. \\
&\quad \left. - 3hT^*\right) = \frac{-b}{4eT^{*2}}T^*\left(\frac{a}{b}-c-hT^*\right) \\
&\quad \cdot\left[\left(\frac{a}{b}-c-hT^*\right)+2h\left(e-T^*\right)\right] \\
&\le 0.
\end{aligned}
\tag{A.2}
$$

B. Derivation Process of $T^{*\prime}(e)$ in Section 4.2

In (23), because T^* varies according to e, T^* is labeled as $T^*(e)$. Partially differentiating e with (23) yields the following formula:

$$
\begin{aligned}
0 &= T^*\left(1-T^{*\prime}(e)\right)\left(\frac{a}{b}-c-hT^*\right)^2 + \left(e-T^*\right) \\
&\quad \cdot T^{*\prime}(e) \\
&\quad \cdot\left[\left(\frac{a}{b}-c-hT^*\right)^2 - 2hT^*\left(\frac{a}{b}-c-hT^*\right)\right] \\
&\quad - \left(e-T^*\right)\left(\frac{a}{b}-c-hT^*\right)^2 T^{*\prime}(e) \\
&\quad - \int_0^{T^*}\left(\frac{a}{b}-c-ht\right)^2 dt + \frac{4A}{b}, \quad \forall e.
\end{aligned}
\tag{B.1}
$$

Thus

$$\frac{\partial T^*}{\partial e} = T^{*\prime}(e) = \frac{4A/b - \int_0^{T^*}\left[(a/b-c-ht)^2 - (a/b-c-hT^*)^2\right]dt}{T^*(a/b-c-hT^*)\left[(a/b-c-hT^*)+2h(e-T^*)\right]}; \quad \text{using (23)}$$
$$= \frac{\int_0^{T^*}\left[(1-t/e)(a/b-c-ht)^2 - (1-T^*/e)(a/b-c-hT^*)^2\right]dt}{T^*(a/b-c-hT^*)\left[(a/b-c-hT^*)+2h(e-T^*)\right]}$$
$$- \frac{\int_0^{T^*}\left[(a/b-c-ht)^2 - (a/b-c-hT^*)^2\right]dt}{T^*(a/b-c-hT^*)\left[(a/b-c-hT^*)+2h(e-T^*)\right]} = \frac{(1/e)\int_0^{T^*}\left[T^*(a/b-c-hT^*)^2 - t(a/b-c-ht)^2\right]dt}{T^*(a/b-c-hT^*)\left[(a/b-c-hT^*)+2h(e-T^*)\right]} \tag{B.2}$$
$$= \frac{T^{*2}(a/b-c-hT^*)^2}{eT^*(a/b-c-hT^*)\left[(a/b-c-hT^*)+2h(e-T^*)\right]}$$
$$- \frac{\left[(1/3h)(a/b-c-hT^*)^3 - (1/12h^2)(a/b-c)^4 + (1/12h^2)(a/b-c-hT^*)^4\right]}{eT^*(a/b-c-hT^*)\left[(a/b-c-hT^*)+2h(e-T^*)\right]}$$
$$= \frac{1}{12}\left(\frac{a}{b}-c-hT^*\right)^2\left(6T^* + \frac{a/b-c-hT^*}{h}\right)\times\left(2T^* - \frac{a/b-c-hT^*}{h}\right) + \frac{(a/b-c)^4}{12h^2}.$$

C. Derivation Process of $T^{*\prime}(h)$ in Section 4.3

By partially differentiating h with (23), the following formula is obtained (see Appendix B for details):

$$\begin{aligned}
0 &= \left(eT^{*\prime}(h) - 2T^*T^{*\prime}(h)\right)\left(\frac{a}{b}-c-hT^*\right)^2 \\
&\quad + T^*(e-T^*)\cdot 2\left(\frac{a}{b}-c-hT^*\right)\times\left(-hT^{*\prime}(h)\right. \\
&\quad \left.-T^*\right) - (e-T^*)\left(\frac{a}{b}-c-hT^*\right)^2 T^{*\prime}(h) \\
&\quad - \int_0^{T^*}(e-t)\cdot 2\left(\frac{a}{b}-c-ht\right)(-t)\,dt = T^{*\prime}(h) \\
&\quad \cdot\left[(e-2T^*)\left(\frac{a}{b}-c-hT^*\right)^2\right. \\
&\quad - 2hT^*(e-T^*)\left(\frac{a}{b}-c-hT^*\right) \\
&\quad \left.- (e-T^*)\left(\frac{a}{b}-c-hT^*\right)^2\right] - 2T^{*2}(e-T^*)\left(\frac{a}{b}\right. \\
&\quad \left.-c-hT^*\right) + 2\int_0^{T^*} t(e-t)\left(\frac{a}{b}-c-ht\right)dt \\
&= T^{*\prime}(h)\left[-T^*\left(\frac{a}{b}-c-hT^*\right)^2\right. \\
&\quad \left.- 2hT^*(e-T^*)\left(\frac{a}{b}-c-hT^*\right)\right] - 2T^{*2}\times(e \\
&\quad -T^*)\left(\frac{a}{b}-c-hT^*\right) \\
&\quad + 2\int_0^{T^*} t(e-t)\left(\frac{a}{b}-c-ht\right)dt, \quad \forall h.
\end{aligned} \tag{C.1}$$

Thus

$$\begin{aligned}
T^{*\prime}(h) &= \frac{-2\int_0^{T^*}\left[T^*(e-T^*)(a/b-c-hT^*) - t(e-t)(a/b-c-ht)\right]dt}{T^*(a/b-c-hT^*)^2 + 2T^*(e-T^*)(a/b-c-hT^*)} \\
&= \frac{-2\left[T^{*2}(e-T^*)(a/b-c-hT^*)\right]}{T^*(a/b-c-hT^*)^2 + 2T^*(e-T^*)(a/b-c-hT^*)} \\
&\quad + \frac{2\left[(a/b-c-hT^*)\left(eT^{*2}/2 - T^{*3}/3\right) - h\left(eT^{*3}/6 - T^{*4}/12\right)\right]}{T^*(a/b-c-hT^*)^2 + 2T^*(e-T^*)(a/b-c-hT^*)} > 0
\end{aligned} \tag{C.2}$$

(verified using Figure 3 and referencing (32) and (33)).

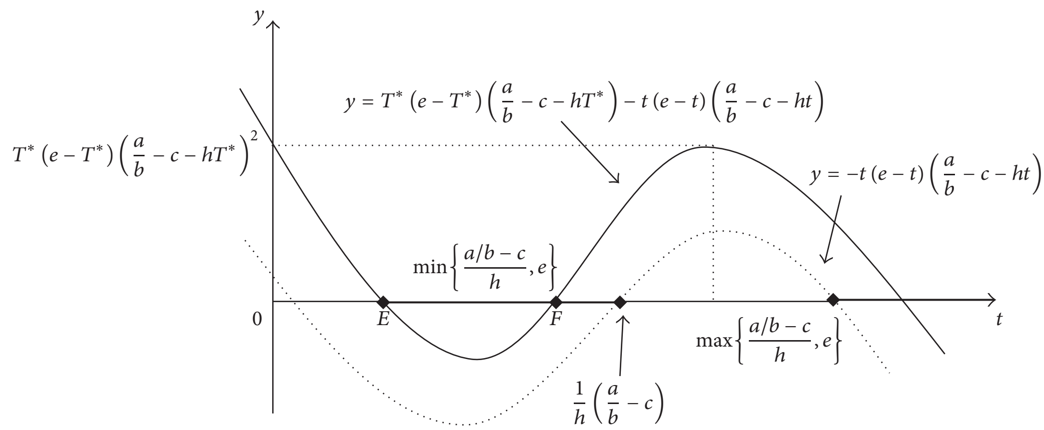

Figure 3: Effect of the increase in h on T^*.

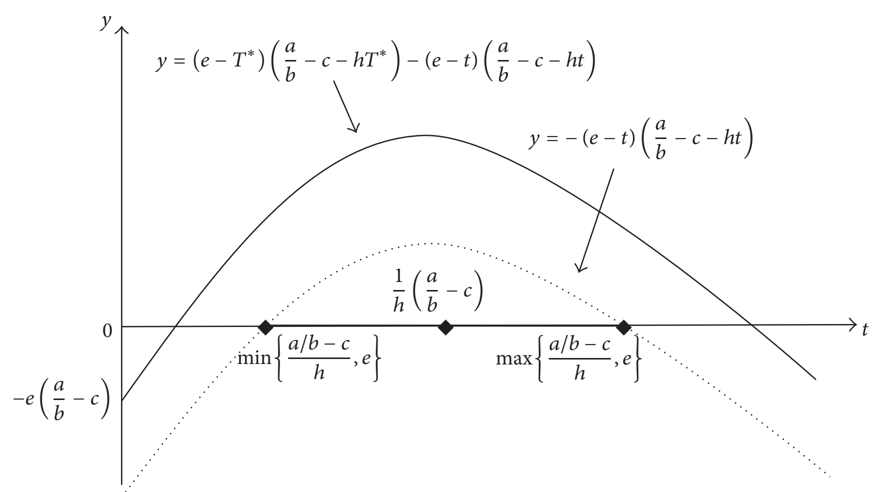

Figure 4: Effect of changes in c on T^*.

D. Derivation Process of $T^{*\prime}(c)$ in Section 4.4

In (23), because T^* varies according to c, T^* is labeled as $T^*(c)$. Partially differentiating c with (23) yields the following formula:

$$\begin{aligned}0 &= T^* (e - T^*) \cdot 2\left(\frac{a}{b} - c - hT^*\right)\left(-1 - hT^{*\prime}(c)\right) + (e - 2T^*) \times T^{*\prime}\left(\frac{a}{b} - c - hT^*\right)^2 - (e - T^*)\left(\frac{a}{b} - c - hT^*\right)^2 \cdot T^{*\prime}(c) \\ &\quad + \int_0^{T^*} \left[(e-t) \cdot 2\left(\frac{a}{b} - c - ht\right)\right] dt = T^{*\prime}(c)\left[-2hT^*(e - T^*)\left(\frac{a}{b} - c - hT^*\right) - T^*\left(\frac{a}{b} - c - hT^*\right)^2 \right. \\ &\quad \left. - 2\int_0^{T^*} \left[(e - T^*)\left(\frac{a}{b} - c - hT^*\right) - (e-t)\left(\frac{a}{b} - c - ht\right)\right] dt\right]. \qquad \text{(D.1)}\end{aligned}$$

Thus

$$T^{*\prime}(c) = \frac{-2\int_0^{T^*} \left[T^*(e - T^*)(a/b - c - hT^*) - (e-t)(a/b - c - ht)\right] dt}{2hT^*(e - T^*)(a/b - c - hT^*) + T^*(a/b - c - hT^*)^2}. \qquad \text{(D.2)}$$

Conflicts of Interest

The author declares that they have no conflicts of interest.

References

[1] B. Wierenga, "Model and measurement methodology for the analysis of consumer choice of food products," *Journal of Food Quality*, vol. 6, no. 2, pp. 119–137, 1983.

[2] J. E. Steenkamp, "Perceived quality of food products and its relationship to consumer preferences: theory and measurement," *Journal of Food Quality*, vol. 9, no. 6, pp. 373–386, 1987.

[3] C. F. Ross, K. Pecka, and K. Weller, "Effect of storage conditions on the sensory quality of ground arabica coffee," *Journal of Food Quality*, vol. 29, no. 6, pp. 596–606, 2006.

[4] S. Tarea, G. Cuvelier, and J. M. Sieffermann, "Sensory evaluation of the texture of 49 commercial apple and pear purees," *Journal of Food Quality*, vol. 30, no. 6, pp. 1121–1131, 2007.

[5] A. Herbon, E. Levner, and T. C. E. Cheng, "Perishable inventory management and dynamic pricing using tti technologies," *International Journal of Innovation, Management and Technology*, vol. 3, no. 3, pp. 262–266, 2012.

[6] A. Herbon, E. Levner, and T. C. E. Cheng, "Perishable inventory management with dynamic pricing using time-temperature indicators linked to automatic detecting devices," *International Journal of Production Economics*, vol. 147, pp. 605–613, 2014.

[7] S. Nahmias, "Perishable inventory theory: a review," *Operations Research*, vol. 30, no. 4, pp. 680–708, 1982.

[8] S. K. Goyala and B. C. Giri, "Recent trends in modeling of deteriorating inventory," *European Journal of Operational Research*, vol. 134, no. 1, pp. 1–16, 2001.

[9] S. Nahmias, *Perishable Inventory Systems*, Springer, Boston, MA, USA, 2011.

[10] I. Z. Karaesmen, A. Scheller-Wolf, and B. Deniz, "Managing perishable and aging inventories: Review and future research directions," *International Series in Operations Research and Management Science*, vol. 151, pp. 393–436, 2011.

[11] M. Bakker, J. Riezebos, and R. H. Teunter, "Review of inventory systems with deterioration since 2001," *European Journal of Operational Research*, vol. 221, no. 2, pp. 275–284, 2012.

[12] L. Janssen, T. Claus, and J. Sauer, "Literature review of deteriorating inventory models by key topics from 2012 to 2015," *International Journal of Production Economics*, vol. 182, pp. 86–112, 2016.

[13] A. Andijani and M. Al-Dajani, "Analysis of deteriorating inventory/production systems using a linear quadratic regulator," *European Journal of Operational Research*, vol. 106, no. 1, pp. 82–89, 1998.

[14] J.-M. Chen and L.-T. Chen, "Pricing and production lot-size/scheduling with finite capacity for a deteriorating item over a finite horizon," *Computers and Operations Research*, vol. 32, no. 11, pp. 2801–2819, 2005.

[15] Z. T. Balkhi and L. Tadj, "A generalized economic order quantity model with deteriorating items and time varying demand, deterioration, and costs," *International Transactions in Operational Research*, vol. 15, no. 4, pp. 509–517, 2008.

[16] H.-J. Chang and P.-Y. Chen, "An EOQ model with controllable selling rate," *Asia-Pacific Journal of Operational Research*, vol. 25, no. 2, pp. 151–167, 2008.

[17] Y. He, S.-Y. Wang, and K. K. Lai, "An optimal production-inventory model for deteriorating items with multiple-market demand," *European Journal of Operational Research*, vol. 203, no. 3, pp. 593–600, 2010.

[18] A. A. Alamri, "Theory and methodology on the global optimal solution to a general reverse logistics inventory model for deteriorating items and time-varying rates," *Computers and Industrial Engineering*, vol. 60, no. 2, pp. 236–247, 2011.

[19] M. Cheng, B. Zhang, and G. Wang, "Optimal policy for deteriorating items with trapezoidal type demand and partial backlogging," *Applied Mathematical Modelling. Simulation and Computation for Engineering and Environmental Systems*, vol. 35, no. 7, pp. 3552–3560, 2011.

[20] K.-C. Hung, "An inventory model with generalized type demand, deterioration and backorder rates," *European Journal of Operational Research*, vol. 208, no. 3, pp. 239–242, 2011.

[21] S.-W. Lin, "Inventory models with managerial policy independent of demand," *European Journal of Operational Research*, vol. 211, no. 3, pp. 520–524, 2011.

[22] K. Gumasta, F. T. S. Chan, and M. K. Tiwari, "An incorporated inventory transport system with two types of customers for multiple perishable goods," *International Journal of Production Economics*, vol. 139, no. 2, pp. 678–686, 2012.

[23] Y. He and S. Wang, "Analysis of production-inventory system for deteriorating items with demand disruption," *International Journal of Production Research*, vol. 50, no. 16, pp. 4580–4592, 2012.

[24] S. Agrawal, S. Banerjee, and S. Papachristos, "Inventory model with deteriorating items, ramp-type demand and partially backlogged shortages for a two warehouse system," *Applied Mathematical Modelling. Simulation and Computation for Engineering and Environmental Systems*, vol. 37, no. 20-21, pp. 8912–8929, 2013.

[25] T. Avinadav, A. Herbon, and U. Spiegel, "Optimal inventory policy for a perishable item with demand function sensitive to price and time," *International Journal of Production Economics*, vol. 144, no. 2, pp. 497–506, 2013.

[26] A. Chauhan and A. P. Singh, "Optimal replenishment and ordering policy for time dependent demand and deterioration with discounted cash flow analysis," *International Journal of Mathematics in Operational Research*, vol. 6, no. 4, pp. 407–436, 2014.

[27] R. Roy Chowdhury, S. K. Ghosh, and K. S. Chaudhuri, "An inventory model for perishable items with stock and advertisement sensitive demand," *International Journal of Management Science and Engineering Management*, vol. 9, no. 3, pp. 169–177, 2014.

[28] M. Amirthakodi, V. Radhamani, and B. Sivakumar, "A perishable inventory system with service facility and feedback customers," *Annals of Operations Research*, vol. 233, pp. 25–55, 2015.

[29] A. K. Bhunia, A. A. Shaikh, G. Sharma, and S. Pareek, "A two storage inventory model for deteriorating items with variable demand and partial backlogging," *Journal of Industrial and Production Engineering*, vol. 32, no. 4, pp. 263–272, 2015.

[30] D. Dutta and P. Kumar, "A partial backlogging inventory model for deteriorating items with time-varying demand and holding cost," *International Journal of Mathematics in Operational Research*, vol. 7, no. 3, pp. 281–296, 2015.

[31] K. V. Geetha and R. Udayakumar, "Optimal replenishment policy for deteriorating items with time sensitive demand under trade credit financing," *American Journal of Mathematical and Management Sciences*, vol. 34, no. 3, pp. 197–212, 2015.

[32] P. Hu, S. Shum, and M. Yu, "Joint inventory and markdown management for perishable goods with strategic consumer behavior," *Operations Research*, vol. 64, no. 1, pp. 118–134, 2016.

[33] C.-Y. Dye, H.-J. Chang, and C.-H. Wu, "Purchase-inventory decision models for deteriorating items with a temporary sale price," *International Journal of Information and Management Sciences*, vol. 18, no. 1, pp. 17–35, 2007.

[34] P. H. Hsu, H. M. Wee, and H. M. Teng, "Preservation technology investment for deteriorating inventory," *International Journal of Production Economics*, vol. 124, no. 2, pp. 388–394, 2010.

[35] J. C. Yu, "Optimal deteriorating items inventory model with a three-echelon supply chain strategic alliance," *Asia-Pacific Journal of Operational Research*, vol. 27, no. 6, pp. 693–711, 2010.

[36] Y.-S. Huang, W.-J. Su, and Z.-L. Lin, "A study on lead-time discount coordination for deteriorating products," *European Journal of Operational Research*, vol. 215, no. 2, pp. 358–366, 2011.

[37] J. Blackburn and G. Scudder, "Supply chain strategies for perishable products: the case of fresh produce," *Production and Operations Management*, vol. 18, no. 2, pp. 129–137, 2009.

[38] T. Avinadav, A. Herbon, and U. Spiegel, "Optimal ordering and pricing policy for demand functions that are separable into price and inventory age," *International Journal of Production Economics*, vol. 155, pp. 406–417, 2014.

[39] P.-Y. Chen, M.-S. Chen, and I.-C. Chen, "The optimal price control model of food sales in a given period," *Journal of Information and Optimization Sciences*, vol. 34, no. 6, pp. 20–31, 2013.

[40] P.-Y. Chen, M.-S. Chen, and C.-Y. Lin, "The inventory model of the effect of product validity on consumer purchase intension," *ICIC Express Letters*, vol. 7, no. 7, pp. 2115–2120, 2013.

[41] E. Bottani, G. Ferretti, R. Montanari, and M. Rinaldi, "Analysis and optimisation of inventory management policies for perishable food products: A simulation study," *International Journal of Simulation and Process Modelling*, vol. 9, no. 1-2, pp. 16–32, 2014.

[42] S.-C. Chen and J.-T. Teng, "Retailer's optimal ordering policy for deteriorating items with maximum lifetime under supplier's trade credit financing," *Applied Mathematical Modelling. Simulation and Computation for Engineering and Environmental Systems*, vol. 38, no. 15-16, pp. 4049–4061, 2014.

[43] S.-C. Chen and J.-T. Teng, "Inventory and credit decisions for time-varying deteriorating items with up-stream and down-stream trade credit financing by discounted cash flow analysis," *European Journal of Operational Research*, vol. 243, no. 2, pp. 566–575, 2015.

[44] O. Boxma, D. Perry, and S. Zacks, "A fluid EOQ model of perishable items with intermittent high and low demand rates," *Mathematics of Operations Research*, vol. 40, no. 2, pp. 390–402, 2015.

[45] X. Chao, X. Gong, C. Shi, and H. Zhang, "Approximation algorithms for perishable inventory systems," *Operations Research*, vol. 63, no. 3, pp. 585–601, 2015.

[46] P. Guchhait, M. K. Maiti, and M. Maiti, "An EOQ model of deteriorating item in imprecise environment with dynamic deterioration and credit linked demand," *Applied Mathematical Modelling. Simulation and Computation for Engineering and Environmental Systems*, vol. 39, no. 21, pp. 6553–6567, 2015.

[47] A. Herbon, "Optimal two-level piecewise-constant price discrimination for a storable perishable product," *International Journal of Production Research*, 2015.

[48] G. Mahapatra, S. Adak, T. Mandal, and S. Pal, "Inventory model for deteriorating items with time and reliability dependent demand and partial backorder," *International Journal of Operational Research*, vol. 29, no. 3, p. 344, 2017.

[49] P. L. Abad, "Optimal pricing and lot-sizing under conditions of perishability, finite production and partial backordering and lost sale," *European Journal of Operational Research*, vol. 144, no. 3, pp. 677–685, 2003.

[50] Y.-C. Tsao and G.-J. Sheen, "Joint pricing and replenishment decisions for deteriorating items with lot-size and time-dependent purchasing cost under credit period," *International Journal of Systems Science. Principles and Applications of Systems and Integration*, vol. 38, no. 7, pp. 549–561, 2007.

[51] C.-T. Chang, J.-T. Teng, and S. K. Goyal, "Inventory lot-size models under trade credits: a review," *Asia-Pacific Journal of Operational Research*, vol. 25, no. 1, pp. 89–112, 2008.

[52] C.-T. Yang, L.-Y. Ouyang, K.-S. Wu, and H.-F. Yen, "An inventory model with temporary price discount when lead time links to order quantity," *Journal of Scientific and Industrial Research*, vol. 69, no. 3, pp. 180–187, 2010.

[53] J. Wu, L.-Y. Ouyang, L. E. Cárdenas-Barrón, and S. K. Goyal, "Optimal credit period and lot size for deteriorating items with expiration dates under two-level trade credit financing," *European Journal of Operational Research*, vol. 237, no. 3, pp. 898–908, 2014.

[54] L. Cheng, C.-S. Tsou, and D.-Y. Yang, "Cost-service tradeoff analysis of reorder-point-lot-size inventory models," *Journal of Manufacturing Systems*, vol. 37, pp. 217–226, 2015.

[55] J.-T. Teng, L. E. Cárdenas-Barrón, H.-J. Chang, J. Wu, and Y. Hu, "Inventory lot-size policies for deteriorating items with expiration dates and advance payments," *Applied Mathematical Modelling. Simulation and Computation for Engineering and Environmental Systems*, vol. 40, no. 19-20, pp. 8605–8616, 2016.

[56] F. Z. Sargut and G. GülIşık, "Dynamic economic lot size model with perishable inventory and capacity constraints," *Applied Mathematical Modelling. Simulation and Computation for Engineering and Environmental Systems*, vol. 48, pp. 806–820, 2017.

[57] P. L. Abad, "Optimal price and order size for a reseller under partial backordering," *Computers and Operations Research*, vol. 28, no. 1, pp. 53–65, 2001.

[58] M.-S. Chen and M.-C. Chu, "The analysis of optimal control model in matching problem between manufacturing and marketing," *European Journal of Operational Research*, vol. 150, no. 2, pp. 293–303, 2003.

[59] A. Chande, S. Dhekane, N. Hemachandra, and N. Rangaraj, "Perishable inventory management and dynamic pricing using RFID technology," *Sadhana*, vol. 30, no. 2-3, pp. 307–316, 2005.

[60] A. Bisi and M. Dada, "Dynamic learning, pricing, and ordering by a censored newsvendor," *Naval Research Logistics*, vol. 54, no. 4, pp. 448–461, 2007.

[61] Y.-C. Tsao and G.-J. Sheen, "Dynamic pricing, promotion and replenishment policies for a deteriorating item under permissible delay in payments," *Computers and Operations Research*, vol. 35, no. 11, pp. 3562–3580, 2008.

[62] E. Berk, Ü. Gürler, and G. Yildirim, "On pricing of perishable assets with menu costs," *International Journal of Production Economics*, vol. 121, no. 2, pp. 678–699, 2009.

[63] E. P. Chew, C. Lee, and R. Liu, "Joint inventory allocation and pricing decisions for perishable products," *International Journal of Production Economics*, vol. 120, no. 1, pp. 139–150, 2009.

[64] Y. Akçay, H. P. Natarajan, and S. H. Xu, "Joint dynamic pricing of multiple perishable products under consumer choice," *Management Science*, vol. 56, no. 8, pp. 1345–1361, 2010.

[65] S. Dasu and C. Tong, "Dynamic pricing when consumers are strategic: analysis of posted and contingent pricing schemes," *European Journal of Operational Research*, vol. 204, no. 3, pp. 662–671, 2010.

[66] R. Maihami and I. N. Kamalabadi, "Joint pricing and inventory control for non-instantaneous deteriorating items with partial backlogging and time and price dependent demand," *International Journal of Production Economics*, vol. 136, no. 1, pp. 116–122, 2012.

[67] A. Herbon, "Dynamic pricing vs. acquiring information on consumers heterogeneous sensitivity to product freshness," *International Journal of Production Research*, vol. 52, no. 3, pp. 918–933, 2014.

[68] A. Herbon, "Optimal piecewise-constant price under heterogeneous sensitivity to product freshness," *International Journal of Production Research*, vol. 54, no. 2, pp. 365–385, 2016.

[69] A. K. Bhunia, A. A. Shaikh, and R. K. Gupta, "A study on two-warehouse partially backlogged deteriorating inventory models under inflation via particle swarm optimisation," *International Journal of Systems Science. Principles and Applications of Systems and Integration*, vol. 46, no. 6, pp. 1036–1050, 2015.

[70] C.-T. Chang, M.-C. Cheng, and L.-Y. Ouyang, "Optimal pricing and ordering policies for non-instantaneously deteriorating items under order-size-dependent delay in payments," *Applied Mathematical Modelling. Simulation and Computation for Engineering and Environmental Systems*, vol. 39, no. 2, pp. 747–763, 2015.

[71] J. Zhang, Y. Wang, L. Lu, and W. Tang, "Optimal dynamic pricing and replenishment cycle for non-instantaneous deterioration items with inventory-level-dependent demand," *International Journal of Production Economics*, vol. 170, pp. 136–145, 2015.

[72] C.-Y. Dye and C.-T. Yang, "Optimal dynamic pricing and preservation technology investment for deteriorating products with reference price effects," *Omega*, vol. 62, pp. 52–67, 2016.

[73] M. Xue, W. Tang, and J. Zhang, "Optimal dynamic pricing for deteriorating items with reference-price effects," *International Journal of Systems Science. Principles and Applications of Systems and Integration*, vol. 47, no. 9, pp. 2022–2031, 2016.

[74] D. J. Saunders, "Thirty years of the inverse problem in the calculus of variations," *Reports on Mathematical Physics*, vol. 66, no. 1, pp. 43–53, 2010.